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Form 1/77

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❶ Title of invention

1 Please give the title of the invention: Three Dimensional Imaging

❷ Applicant's details

❑ **First or only applicant**

2a If you are applying as a corporate body please give:

Corporate name: Toshiba Research Europe Limited

Country *(and State of incorporation, if appropriate)*: United Kingdom

2b If you are applying as an individual or one of a partnership please give in full:

Surname

Forenames

2c **In all cases**, please give the following details:

Address:
Cambridge Research Laboratory,
260 Cambridge Science Park, Milton Road,
Cambridge, CB4 4WE, United Kingdom
United Kingdom

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ADP number *(if known)* 7514136002

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Continuation sheets for this Patents Form 1/77	—
Claim(s)	4
Description	13
Abstract	1
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Three Dimensional Imaging

The present invention relates to the field of imaging samples with radiation in the infra-red (IR) frequency range. More specifically, the present invention relates to apparatus and methods for imaging samples in three dimensions using electromagnetic radiation in the higher Gigahertz (GHz) and the Terahertz (THz) frequency ranges. However, in this type of imaging technology, all such radiation is colloquially referred to as THz radiation, especially that in the range from 200GHz to 84THz.

Recently, there has been much interest in using THz radiation to look at a wide variety of samples using a range of methods. THz radiation has been used for both imaging samples and obtaining spectra. Recently, work by Mittleman *et al*, IEEE Journal of Selected Topics in Quantum Electronics, Vol. 2, No. 3, September 1996, page 679 to 692 illustrates the use of using THz radiation to image various objects such as a flame, a leaf, a moulded piece of plastic and semiconductors.

THz radiation penetrates most dry, non metallic and non polar objects like plastics, paper, cardboard and non polar organic substances. Therefore, THz radiation can be used instead of x-rays to look inside boxes, cases etc. THz has lower energy, non-ionising photons than X-rays, hence, the health risks of using THz radiation are expected to be vastly reduced compared to those using conventional X-rays.

A useful tool in almost all analysis techniques whether medical or otherwise is the ability to produce a three dimensional image of both the internal and external structure of a sample. The use of THz for producing the internal structure of a flat object (a floppy disc) has been described in EP 0 864 857. Here, the inventors

measured reflection of a beam of THz radiation to produce an image of the internal structure of the sample.

However, this method is not suitable for obtaining 3D images of objects where the front and back surfaces are curved. This is for a number of reasons, a main one being that the spatial resolution using this technique is determined by the diffraction limit.

The present invention addresses the above problems and, in a first aspect provides a method of imaging a sample, the method comprising the steps of :

(a) irradiating the sample to be imaged with a beam of pulsed electro-magnetic radiation with a plurality of frequencies in the range from 50 GHz to 84 THz, wherein the beam diameter is narrower than the smallest wavelength of the beam;

(b) detecting radiation from the sample; and

(c) generating an image of the sample from radiation detected in step (b).

Due to the beam diameter being smaller than the wavelength of the radiation, the present invention utilises near-field diffraction techniques. Hence, the spatial resolution is not determined by the focused spot size of the THz beam.

The radiation detected in step (b) could be either that reflected from the sample or radiation which has been transmitted by the sample. In addition to using near field reflection imaging, it is preferable if the method of the present invention also utilises near field transmission techniques. Therefore, preferably, step (b) of the first aspect of the present invention comprises detecting radiation which is both transmitted through and reflected by the sample. The step of generating the image can then be performed on the basis of information from both the reflected and transmitted THz radiation.

Collecting both the reflected and transmitted radiation using the near field technique allows a greater range of curved surfaces to be measured. Hence, the method of the present invention is capable of imaging a sample of virtually any shape.

Radiation which is transmitted from the sample is primarily used to measure the positions of dielectric surfaces within the sample which is to be imaged. Radiation transmitted from the sample is primarily used to determine the sample shape and the composition. This technique allows the curvature of both internal and external surfaces to be measured. Thus, using both reflected and transmitted radiation is an extremely powerful tool to determine the three dimensional structure of the object regardless of whether or not imaging takes place in the near field. Obviously, it is preferable if the sample is imaged in the near field regime.

Thus, in a second aspect, the present invention provides a method of imaging a sample, the method comprising the steps of:-

a) irradiating a sample to be imaged with a beam of pulsed electromagnetic radiation with a plurality of frequencies in the range from 50GHz to 84THz;

b) detecting radiation which is both transmitted through and reflected from the sample; and

c) generating an image of the sample from radiation detected in step (b).

Preferably, according to the second aspect of the present invention, the THz beam diameter is narrower than the smallest wavelength of the beam.

It is preferable to use transmission data to determine the overall shape. In reflection measurements, the beam is not reflected back along the incident radiation axis if the surface is curved. Therefore, only surfaces which very small curvatures can be analysed using only reflection.

In the method of the first aspect and a preferred embodiment of the second aspect, of the present invention, the beam of THz radiation is narrow. Preferably this narrow beam is achieved by illuminating a frequency conversion member with visible radiation with a beam with the diameter of the required THz beam.

To obtain an image of the whole sample, the sample is preferably subdivided into a 2 dimensional pixel array. The radiation which is either reflected by or transmitted through each pixel is detected. The image is then generated pixel by pixel.

Preferably, the sample which is to be imaged is placed on a motorised stage, which can be stepped in the both the x and y directions. The image of the whole area of the sample can then be built up pixel by pixel.

Above it has been mentioned that there is a problem with reflection imaging of curved surfaces because the reflected beam is not reflected back along the same axis as the incident beam, this makes detection of the reflected beam difficult. In previous THz beam detection methods, for example, please see application no.9904166.7, the THz beam is focused to a point for detection. To address the problem of loss of information in the reflected radiation, in a third aspect, the present invention provides a method of imaging a sample, the method comprising the steps of:

a) irradiating a sample to be imaged with a beam of pulsed electromagnetic radiation with a plurality of frequencies in the range from 50GHz to 84THz;

b) detecting radiation reflected from the sample with a CCD camera; and

c) generating an image of the sample using the radiation elected in step (b).

Also, using conventional coherent THz detection methods, for example, electro-optic sampling and photoconductive detection, the THz beam must be focused to a

point and thus information is lost about the path the different THz beams take following reflection. This problem can be addressed by using a CCD camera. Therefore, it is preferable is a CCD camera is used to detect the reflected THz beams. This detection method allows refection techniques to map out the shape of curved surfaces, also, it would be possible to map out differences in shape between internal and external dielectric surfaces.

Also, when collecting the output light using an off axis parabolic mirror, there is a slight time delay due to the different optical path lengths between the centre and the fringe of the mirror. Consequently, the different path lengths of the reflected beams cause the pulses to arrive at different times at the detector. This causes a problem, because it is not easy (if at all possible) to distinguish between a time-shift the pulse due to the position of an internal dielectric layer and a time shift which is a combination between a dielectric mirror and a different path length due to one of the optical mirrors. This problem can also be addressed by the use of a CCD camera as a detector. A CCD camera can be used to image a 2D region containing all the reflected THz beams, both the temporal and spatial shift if the THz can be measured. In other words, more exact information about the sample can be gained by using a CCD camera.

In the methods of the present invention, data can be derived by using the time-of-flight method. As the enters the sample, its velocity changes due to variations in the refractive index of the sample. Thus, by measuring the time of flight of the pulse through the sample, an image of the sample can be obtained using transmission.

Using the frequency domain analysis techniques of UK application no 9940166.7, the composition of the structure can be determined. In this application, a single frequency from the plurality of transmitted or reflected plurality of frequencies is used to generate the image. In some cases, a narrow range of frequencies or a selection of specific frequencies or frequency ranges is studied. The composition of the structure can be determined using the actual magnitude of the signal for a specific or selection of frequencies pixel by pixel.

Thus, complex images can be produced. This system is particularly useful in the detection of breast cancer where both spatial information and compositional information concerning the 3D structure of the breast can be derived.

The method of the present invention allows the internal composition, shape and the position of the internal surfaces to be determined. Hence, a three dimensional image of the sample can be produced from the methods of the three aspects of the present invention. In a fourth aspect, the present invention provides an apparatus for obtaining an image of a sample, the apparatus comprising

a) means for irradiating a sample to be imaged with a beam of pulsed electromagnetic radiation with a plurality of frequencies in the range from 50GHz to 84THz;

b) means for detecting radiation reflected from the sample with a CCD camera; and

c) means for generating an image of the sample using the radiation detected in step (b).

In a fifth aspect, the present invention provides an apparatus for imaging a sample, the apparatus comprising:

(a) means for irradiating the sample to be imaged with a beam of pulsed electro-magnetic radiation with a plurality of frequencies in the range from 50 GHz to 84 THz, wherein the beam diameter is narrower than the smallest wavelength of the beam;

(b) means for detecting radiation from the sample; and

(c) means for generating an image of the sample from radiation detected in step (b).

Preferably, in the apparatus of the present invention, the THz beam is produced by illuminating a THz generation crystal with visible light which has a beam diameter which is smaller than that of the wavelength of the emitted THz radiation. More preferably, the sample is located on the THz generation crystal.

In a sixth aspect, the present invention provides an apparatus for imaging a sample, the apparatus comprising:-

a) means for irradiating a sample to be imaged with a beam of pulsed electromagnetic radiation with a plurality of frequencies in the range from 50GHz to 84THz;

b) means for detecting radiation which is both transmitted through and reflected from the sample; and

c) means for generating an image of the sample from radiation detected in step (b).

The present invention will now be described with reference to the following preferred non-limiting embodiments, shown in the following drawings in which:

Figure 1 shows a near-field transmission and refraction imaging system for THz;

Figure 2 shows a schematic diagram of the complete system of Figure 1 showing both the source and the detectors;

Figure 3 shows a variation of the detection system of Figure 2;

Figure 4 shows a full system using electro-optical detection methods;

Figure 5 shows a full detection system using photoconductive detection;

Figure 6 shows a full system using a CCD camera for detection;

Figure 7 shows a variation on the detection system of Figure 8;

Figure 8 shows a variation on the detection system of Figures 6 and 7;

Figure 9 shows a three-dimensional image of pork skin;

Figure 10 shows three-dimensional images of a toothbrush;

Figure 11 shows three-dimensional THz images of bone samples; and

Figure 12 shows three-dimensional THz images of a tooth.

Figure 1 shows a detail of a near-field transmission and reflection imaging system. A focus visible beam (which has a wavelength in the visible electro-magnetic region) 1 is focused onto a THz generation crystal 3. The THz generation crystal is a crystal with non-linear properties which will emit radiation in the THz regime (50GHz to 84THz) when irradiated by visible light. The THz pulse 5, is emitted from the THz generation crystal 3.

The diameter of the visible beam 1 which impinges on the THz generation crystal, is smaller than that of the smallest wavelength which will be generated in the THz pulse from the generation crystal 3. The sample 7, is directly mounted onto the generation crystal 3. Therefore, the sample is imaged with a beam of THz radiation which has a

beam diameter which is less than that of the smallest wavelength of the THz light. This means that the resolution of the image obtained from the sample will not be limited by the diffraction limit. Part of the THz pulse will be transmitted through the sample 7. The transmitted THz is denoted by Figure 9. THz pulses will also be reflected from the sample. In this specific example, the first refraction of THz pulses occurs at the interface 11 between the sample 7 and the generation crystal 3. A second dielectric interface 13 within the sample 7 causes reflection of R_2 which is the second reflected THz pulse. This pulse will be reflected at a time $\Delta\tau_1$ the third reflection O_3 occurs as the THz pulse leaves the sample 7. By collecting both the reflected and transmitted pulses, considerable detail about the sample 7 can be determined.

Figure 2 shows a complete system. For convenience, like numerals denote like components. Pulse laser source 21 provides the near beam of visible light 1. The beam of light 1 impinges on beams splitter 23. Beam splitter 23 passes a part of the visible pulse 25 towards the sample and a second part of the visible pulse 27 is reflected towards the detection mechanism. Initially looking at the visible beam 25, this is first passed through an off axis parabolic mirror. The off axis parabolic mirror 29 has a hole to allow transmission of the visible pulse therethrough. The pulse is then directed onto the THz generator 3 as shown in Figure 1.

As explained for Figure 1, the THz pulse is then reflected off the external surfaces on dielectric internal surfaces of the sample 7. This reflected pulse 31 is then collected by off axis parabolic mirror 29. The mirror 29 reflects the pulse into THz detector 33 which is used to produce the image. A second off axis parabolic mirror 35 is used to collect the transmitted THz pulse 37 from the sample 7. The off axis parabolic mirror 35 directs the transmitted pulse onwards transmitted pulse THz detector 39. To analyse the temporal shift of the detected data, visible pulse 27 is directed via mirrors, 43, 45 and 47 into THz detectors 33 and 39. An optical delay line 49 is provided to synchronise the visible pulse 27 with the collected reflected and transmitted THz radiation.

Figure 3 shows a variation of the imaging system of Figure 2. Figure 3, is very similar to Figure 2. However, here, the generation beam 25 is delivered using a dichoric beam splitter 51. The beam splitter is ideally 100% reflective to the visible light but 100% transparent to the reflected THz beam. In this arrangement, the dichoric mirror 51 reflects the beam onto the off axis parabolic mirror 29. Because the visible beam 25 is being reflected from the off axis parabolic mirror, this off axis parabolic mirror 29 can be used to focus the beam to a small diameter (about 100 microns) on the generation crystal 3. The reflected THz pulse 31 through the off axis parabolic mirror 29, through the dichoric mirror 51 and into the THz detector for reflected THz 33.

Otherwise, Figure 3 is identical to that of Figure 2.

Figure 4 shows a full detection system using electro-optical detection. The system is largely identical to that of Figure 2. However here, the THz detectors 33 and 39 are shown in more detail. Detection systems 33 and 39 are identical. Therefore, for simplicity only detection system 33 would be described. The THz beam carrying the reflected sample information 101 and a visible light beam 27 are combined using off axis parabolic mirror 103. The off axis parabolic mirror 103 has a hole for the transmission of the visible beam 27 therethrough. Both the visible beam 27 and the reflected beam 101 are then directed onto a THz detection crystal 105. The visible light beam 27 acts as a reference beam which is incident on the detection crystal 105. Each of the axes has distinct refractive indices n_o and n_e along the ordinary and extraordinary axis of crystal 105 respectively. In the absence of a second THz radiation beam 101, the linearly polarised reference beam 27 passes through the detection crystal 105 with negligible change and is polarisation.

The applicant wishes to clarify that although the angle through which the polarisation is rotated by is negligible, the linearly polarised beam can become slightly elliptical. This affect is compensated for by a variable retardation wave plate, eg. a quarter wave plate 107. The emitted beam is converted into circularly polarised light using the quarter wave plate 107. This is then split into two linearly polarised beam by a beam splitter

such as a Wollaston prism 109 which directs the two orthogonal components of the polarised beam onto a balanced photodiode assembly 111. The balanced photodiode signal is adjusted using wave plate 107 such that the difference in outputs between the two diodes is 0.

However, if the detector 107 also detects a secondary beam 101 (in this case a beam with a frequency in the THz range) as well as the reference beam, the angle through which the polarisation is rotated is negligible. This is because the THz electric field modifies the refractive index of the visible (fundamental) radiation along one of the axes n_e, n_o. This results in the visible field after the detector 105 being elliptical and hence the polarisation component separated by the prism 109 are not equal. The difference in the voltage between the output diodes gives a detection voltage.

The reference beam 27 and the THz beam 101 should stay in place as they pass through the crystal 105. Otherwise, the polarisation rotation is obscured. Therefore, the detection crystal 105 has phase matching means to produce a clear signal.

The optical delay is introduced by cube mirror 121 and plain mirror 123. Cube mirror 121 moves in order to match the phase of the THz pulse and the reference beam.

Figure 5 shows a variation on the system of Figure 4. Here, photoconductive detection by photoconductive THz detectors 131 and 133 are used to detect the transmitted and reflected THz beam.

The system shown in Figures 4 and 5, the systems have a single optical delay line that services both detection elements. Alternatively, a separate delay line or each detection element could be used. This may be necessary when very thick objects are imaged and therefore, the transmitted THz pulse would experience a longer delay than the pulse reflected from the front surface.

In a THz beam is incident on a curved surface, i.e. one with a surface normal not parallel to the direction of the THz beam, the THz beam will not be reflected along the same axis. Instead, it would be reflected at an angle which increases with the surface curvature. Therefore, there will be a limited range of surface curvatures that can be probed using conventional methods. In the above systems, in transmission measurements essentially, the off axis parabolic mirror 35 had to be carefully aligned to ensure efficient collection of the transmitted THz beam.

In the two above THz detection methods, the THz must be focused to a point and thus information is lost about the path the different THz beams take following reflection, information can be lost using these methods.

Figure 6 shows a system which uses a CCD camera which can measure all the THz beams that deviate by large distances from the main axis of the THz beam. The system of Figure 6 uses a CCD camera to measure these large deviations.

Also, when collecting the output using an off axis parabolic mirror, there is a slight time delay due to the different optical path lengths between the center and the fringe and the mirror. Consequently, the different path lengths reflected beams would cause the pulses to arrive at different times at the detector. Using the detection methods of Figures 4 and 5, the beams are focused to a single point. This causes a problem as it is difficult (if not impossible) to discriminate between a time shift due to the opposition of dielectric layer and a time shift that is a combination of the dielectric position and a different paths length on the mirror. The effects of different paths to the mirror are greatest when the surfaces/interfaces are sharply curved. However, if we use a CCD camera both the temporal and spatial shift of the THz beam can be measured and this allows the exact curvature of the sample pixel by pixel to be determined.

The Figure 6, shows a similar system to that of Figures 4 and 5. The difference is caused by the detection mechanism. The reference beam 27 and the reflected 101 and

transmitted THz pulses are incident on detector crystal 141. The detected output is then provided to a CCD camera 143 (reflected) or 145 (transmitted).

Figure 7 shows a variation on the system of Figure 6. The off axis parabolic mirrors 29 and 35 are provided with a single hole. Thus, the reference beam 27 can be combined with the transmitted and reflected THz beams without a dichoric beam splitter. This system is much more compact and hence reduces effects arising from the diversion nature of the THz beams.

Figure 8 shows a slight variation on the system of Figure 7. Here, a single CCD camera 151 is used to detect both the reflected and transmitted images simultaneously.

Figure 9 shows 3-dimensional imaging of pork skin thickness using temporal shifts. The 3-D images show that the sample can be viewed from different perspectives. Both compositional data and the shape of the sample can be determined from the collected THz data.

Figure 10 shows a 3-D dimensional THz image of a toothbrush. The image was obtained using a pixel by pixel image using time of flight measurements of the transmitted THz beam.

Figure 11A shows an example of two chicken bones shown in visible image. Figure 11B shows a 3-D THz image through the two bone samples.

Figure 12 shows an image of a tooth both in visible light and using THz. The THz image of the tooth was constructed using time of flight of transmitted radiation in order to obtain the shape. The composition of the tooth was determined using frequency domain measurement such as those described in UK patent application no. 9940166.7 filed by the same applicant.

CLAIMS:

1. A method of imaging a sample, the method comprising the steps of :

(a) irradiating the sample to be imaged with a beam of pulsed electro magnetic radiation with a plurality of frequencies in the range from 50 GHz to 84 THz, wherein the beam diameter is narrower than the smallest wavelength of the beam;

(b) detecting the radiation from the sample;

(c) generating an image of the sample from the radiation detected in step (b).

2. A method according to claim 1, wherein step (b) comprises the step of detecting both radiation transmitted through the sample and radiation reflected from the sample.

3. A method according to claim 1, wherein step (b) comprises the step of detecting transmitted radiation.

4. A method according to claim 1, wherein step (b) comprises the step of detecting reflected radiation.

5. A method according to any preceding claim, wherein in step (b), an area of the sample which is to be imaged is subdivided into a two-dimensional array of pixels, and radiation is detected from each pixel.

6. A method of imaging a sample, the method comprising the steps of:-

a) irradiating a sample to be imaged with a beam of pulsed electromagnetic radiation with a plurality of frequencies in the range from 50GHz to 84THz;

b) detecting radiation which is both transmitted through and reflected from the sample; and

c) generating an image of the sample from radiation detected in step (b).

Preferably, according to the second aspect of the present invention, the THz beam diameter is narrower than the smallest wavelength of the beam.

7. A method of imaging a sample, the method comprising the steps of:

a) irradiating a sample to be imaged with a beam of pulsed electromagnetic radiation with a plurality of frequencies in the range from 50GHz to 84THz;

b) detecting radiation reflected from the sample with a CCD camera; and

c) generating an image of the sample using the radiation elected in step (b).

8. A method according to any preceding claim, wherein in step (b), an area of the sample is subdivided into a two dimensional array of pixels, and detecting the radiation from each pixel.

9. A method according to any preceding claim wherein a three dimensional image is generated in step (c).

10. A method according to claim 9, wherein only reflected radiation is used to generate the 3D image.

11. A method according to claim 9, wherein only transmitted radiation is used to generate the 3D image.

12. A method according to claim 9, wherein both transmitted and reflected radiation is used to generate the 3D image.

13. A method according to any preceding claim, wherein the optics are configured to obtain maximum resolution.

14. An apparatus for obtaining an image of a sample, the apparatus comprising

a) means for irradiating a sample to be imaged with a beam of pulsed electromagnetic radiation with a plurality of frequencies in the range from 50GHz to 84THz;

b) means for detecting radiation reflected from the sample with a CCD camera; and

c) means for generating an image of the sample using the radiation detected in step (b).

15. An apparatus for imaging a sample, the apparatus comprising:

(a) means for irradiating the sample to be imaged with a beam of pulsed electro-magnetic radiation with a plurality of frequencies in the range from 50 GHz to 84 THz, wherein the beam diameter is narrower than the smallest wavelength of the beam;

(b) means for detecting radiation from the sample; and

(c) means for generating an image of the sample from radiation detected in step (b).

16. An apparatus for imaging a sample, the apparatus comprising:-

a) means for irradiating a sample to be imaged with a beam of pulsed electromagnetic radiation with a plurality of frequencies in the range from 50GHz to 84THz;

b) means for detecting radiation which is both transmitted through and reflected from the sample; and

c) means for generating an image of the sample from radiation detected in step (b).

ABSTRACT:

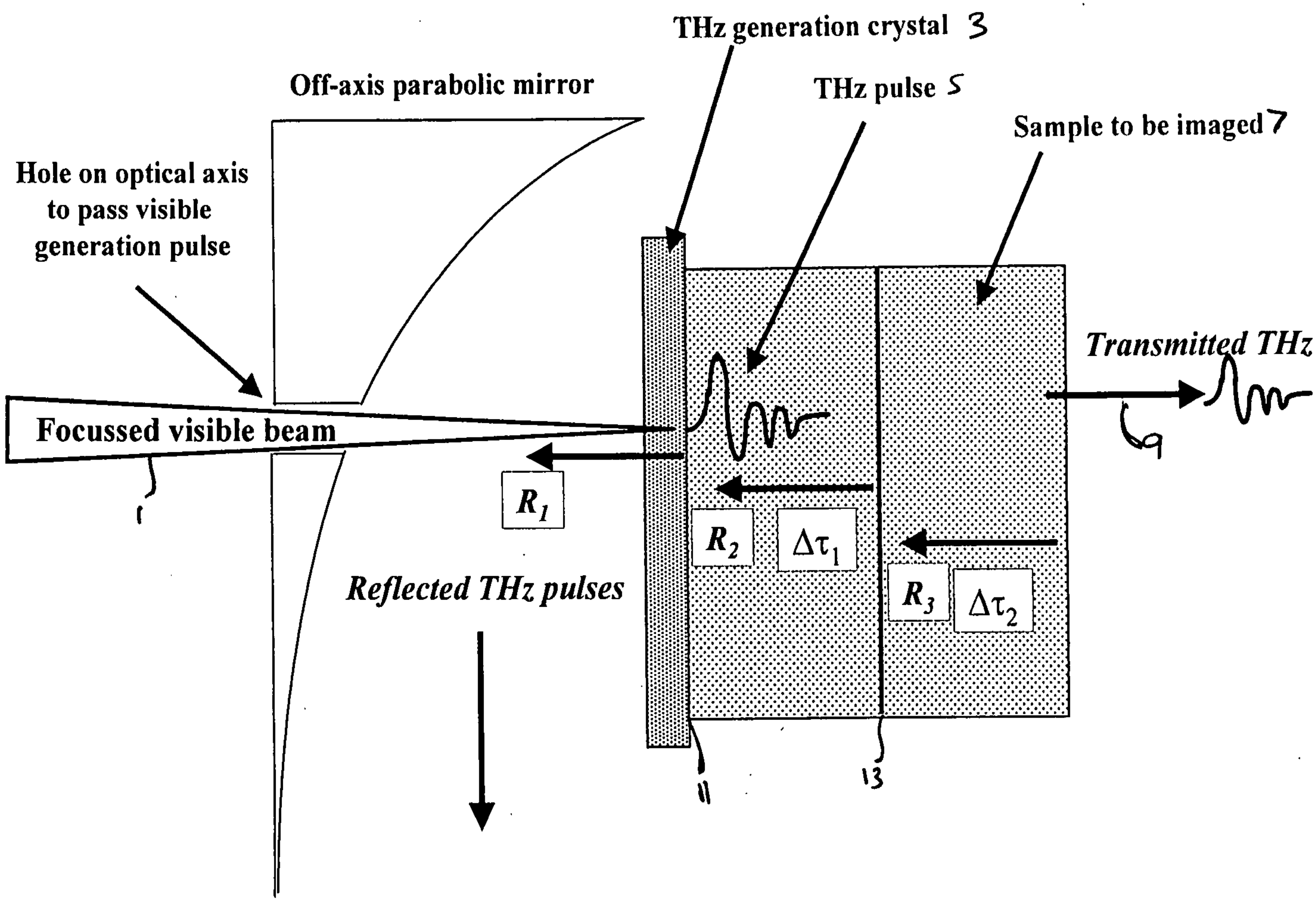
A method and apparatus for imaging a sample, the method comprising the steps of:-

a) irradiating a sample to be imaged with a beam of pulsed electromagnetic radiation with a plurality of frequencies in the range from 50GHz to 84THz;

b) detecting radiation which is both transmitted through and reflected from the sample; and

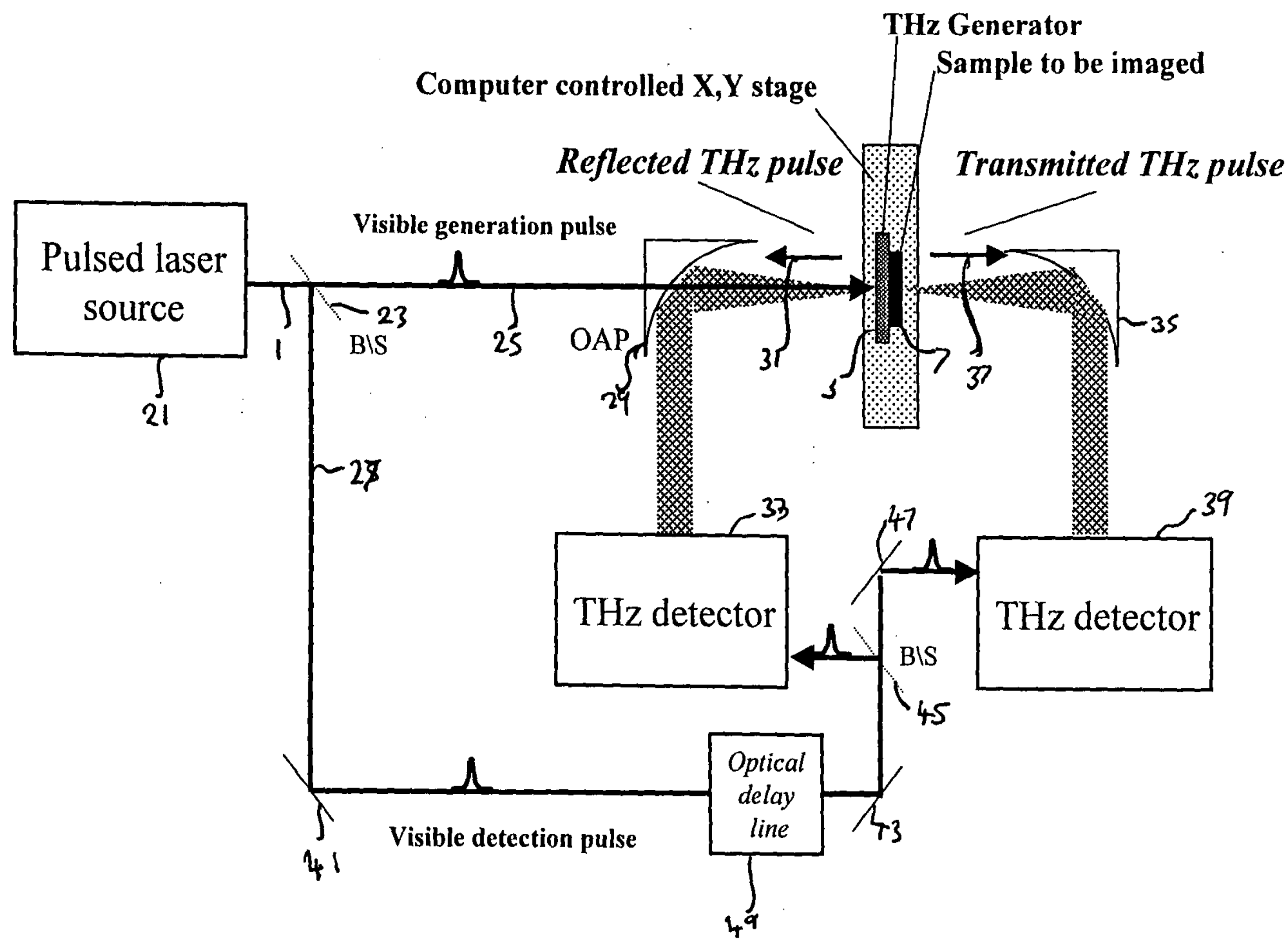
c) generating an image of the sample from radiation detected in step (b).

Figure 1: Detail of near-field transmission & reflection imaging



Version 3cc : June 99

Figure 2: Simultaneous Near-field Transmission & Reflection THz Imag



Version 3cc : June 99

Figure 3: Simultaneous Near-field Transmission & Reflection THz Imag

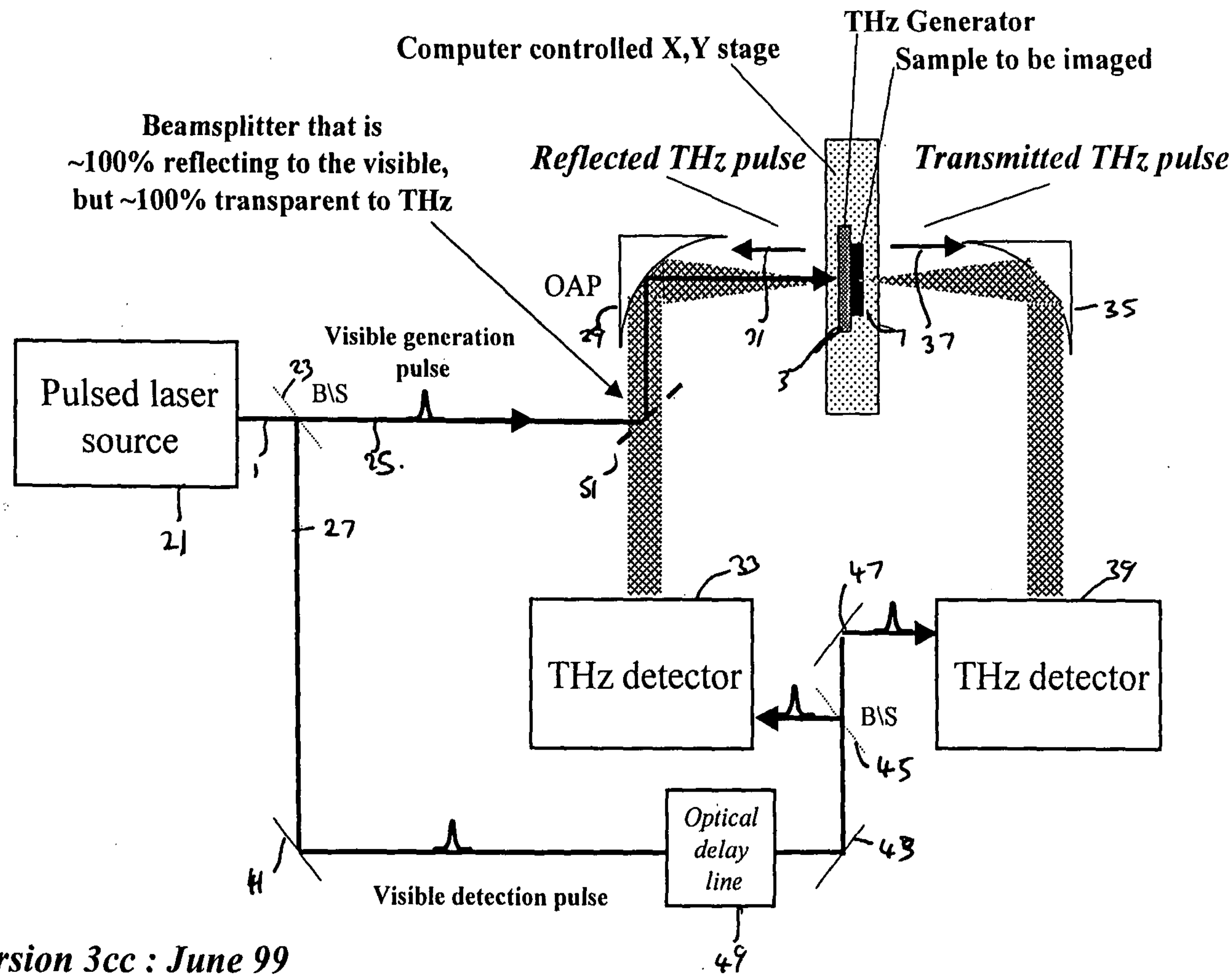


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Figure 4: Full system - using electro-optical detection

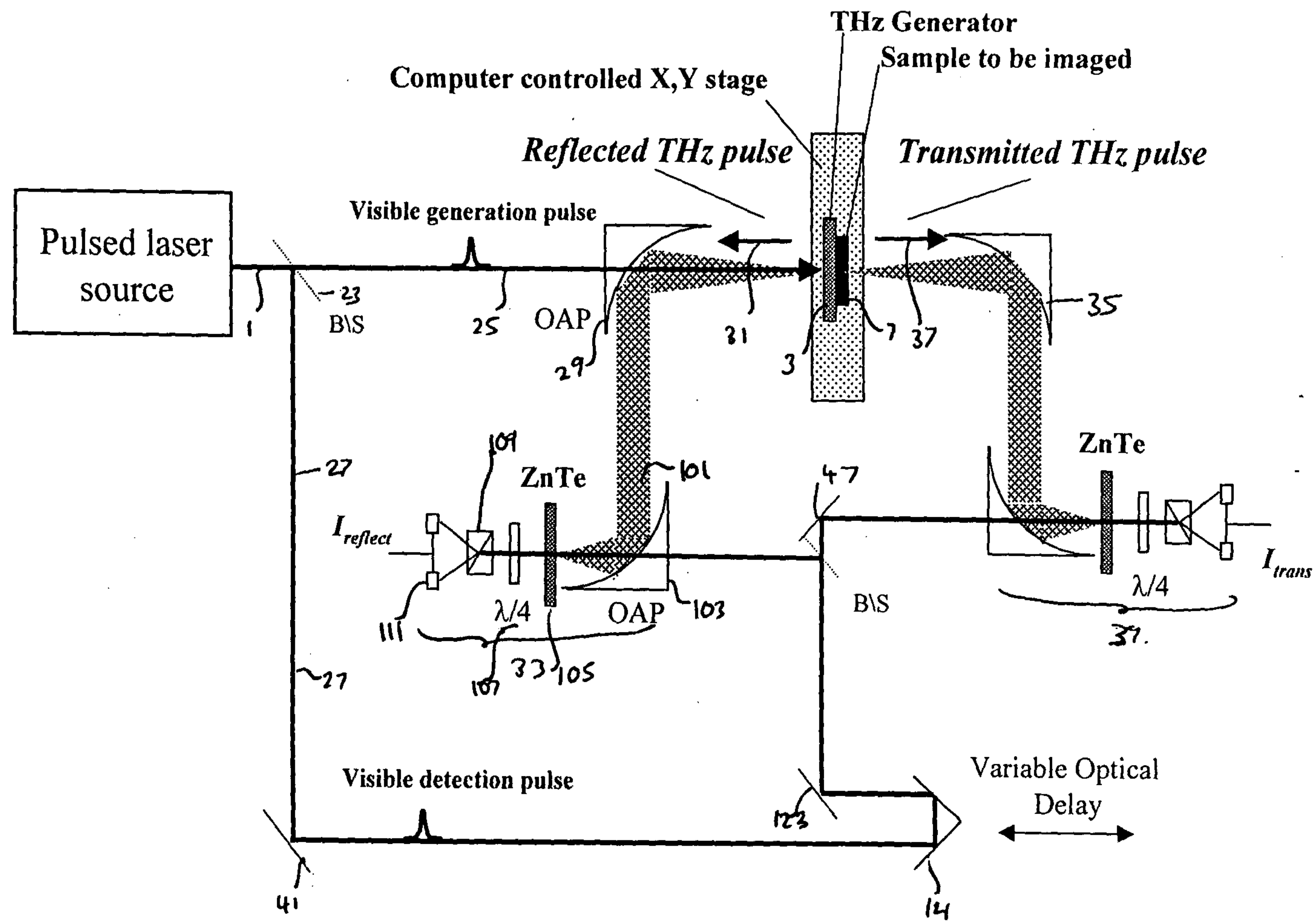

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Figure 5: Full system - using photoconductive detection

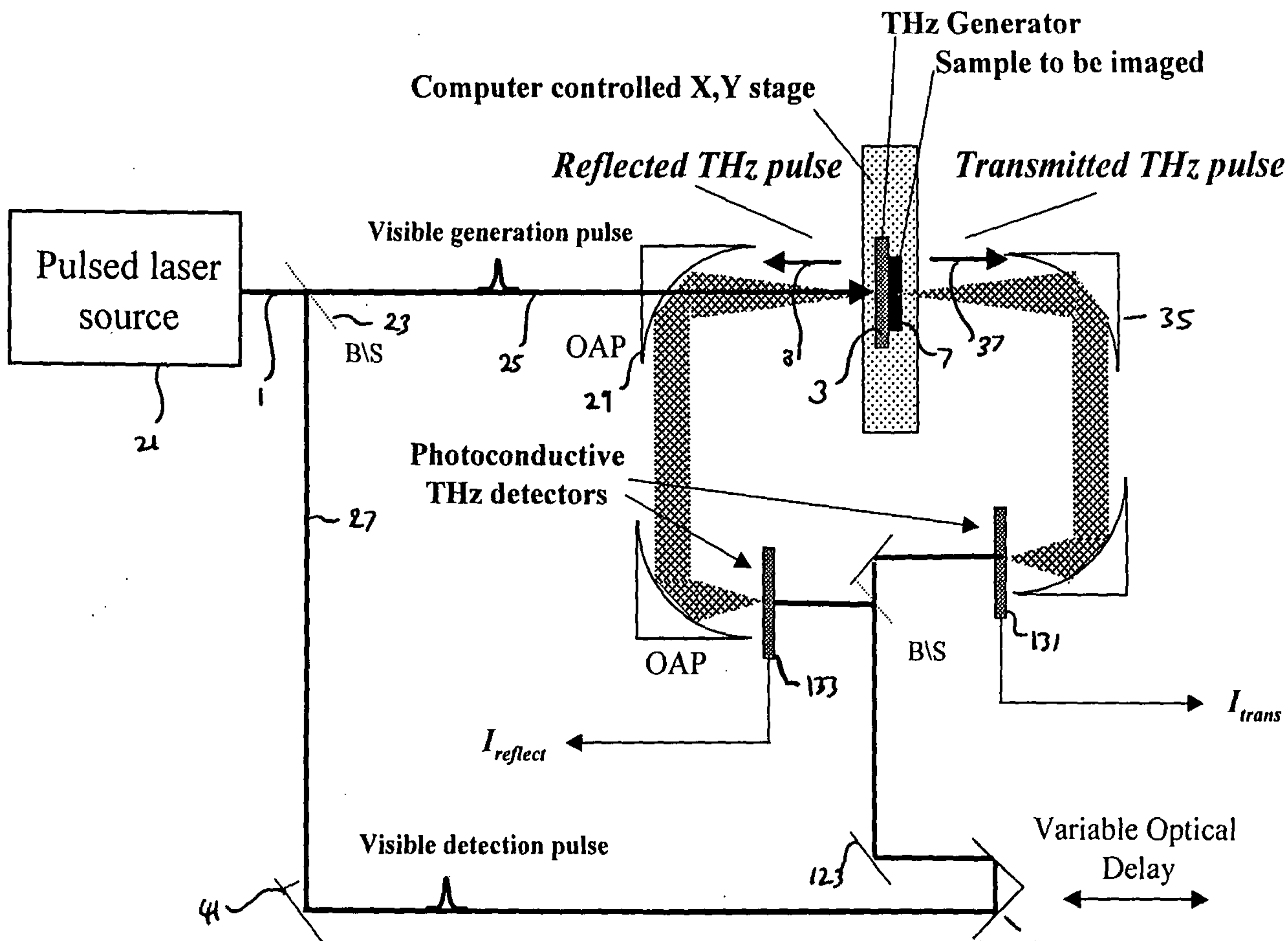

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Figure 6: Full system - using CCD Camera detection

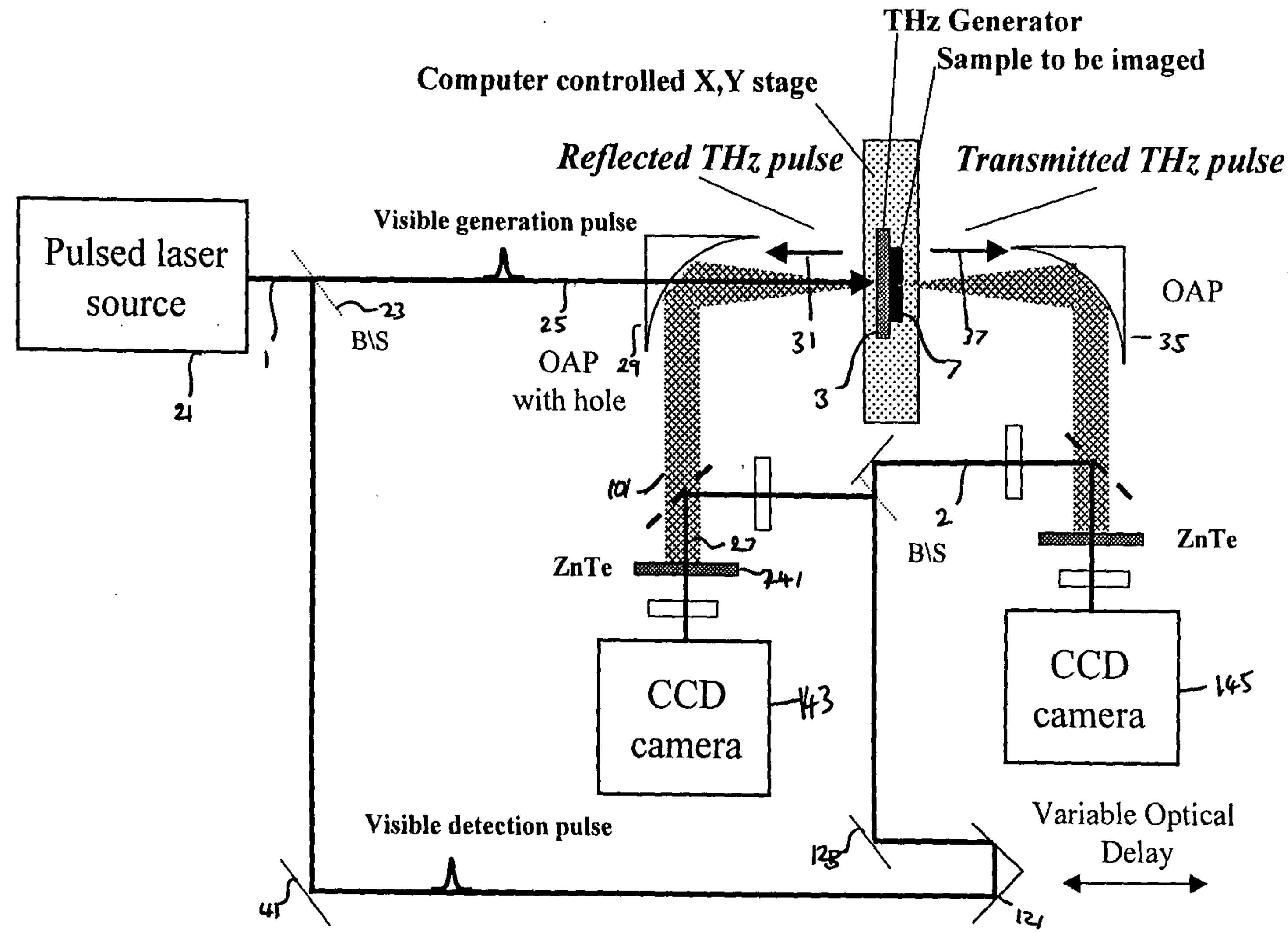

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Figure 7: Full system - using CCD Camera detection - version 2

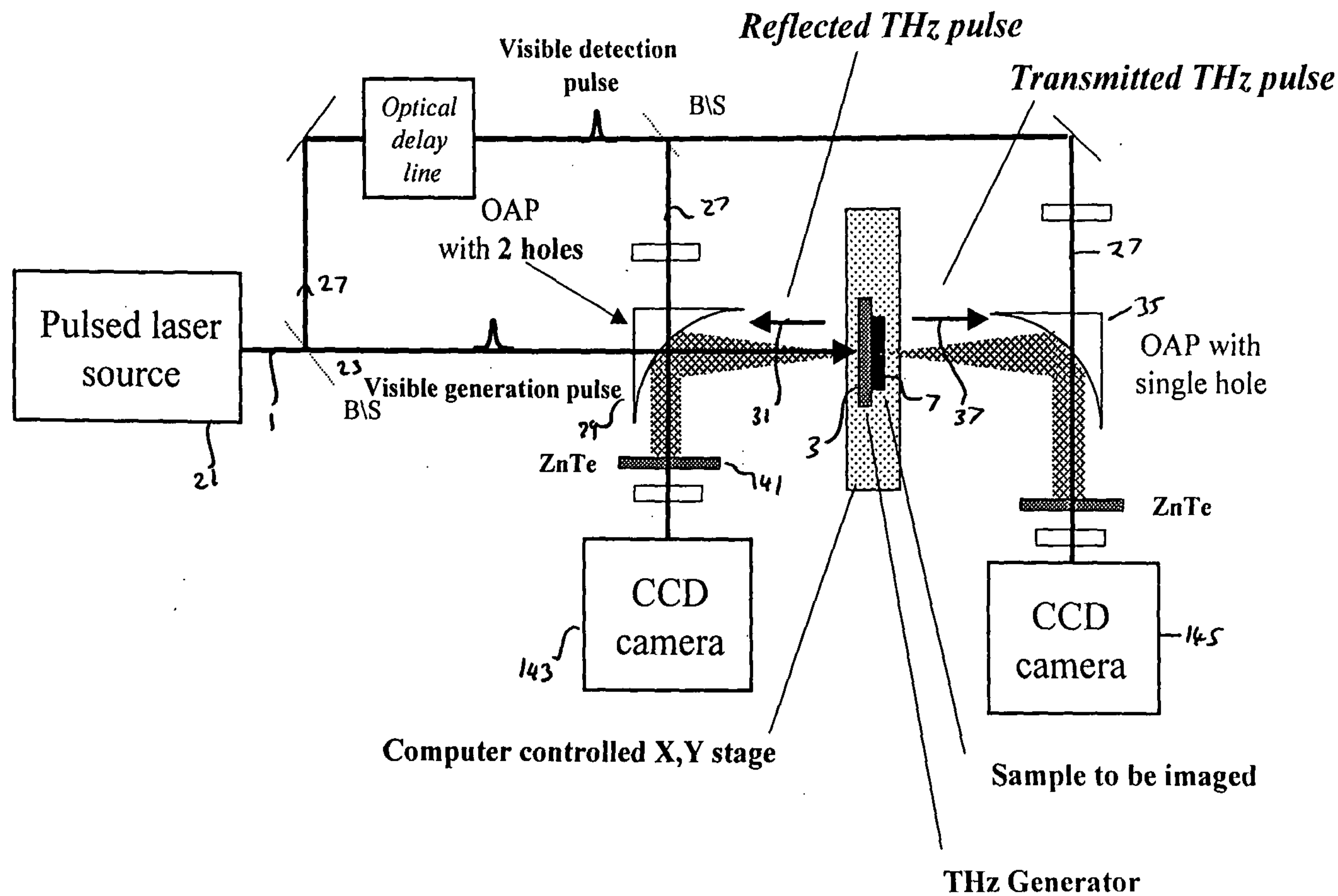

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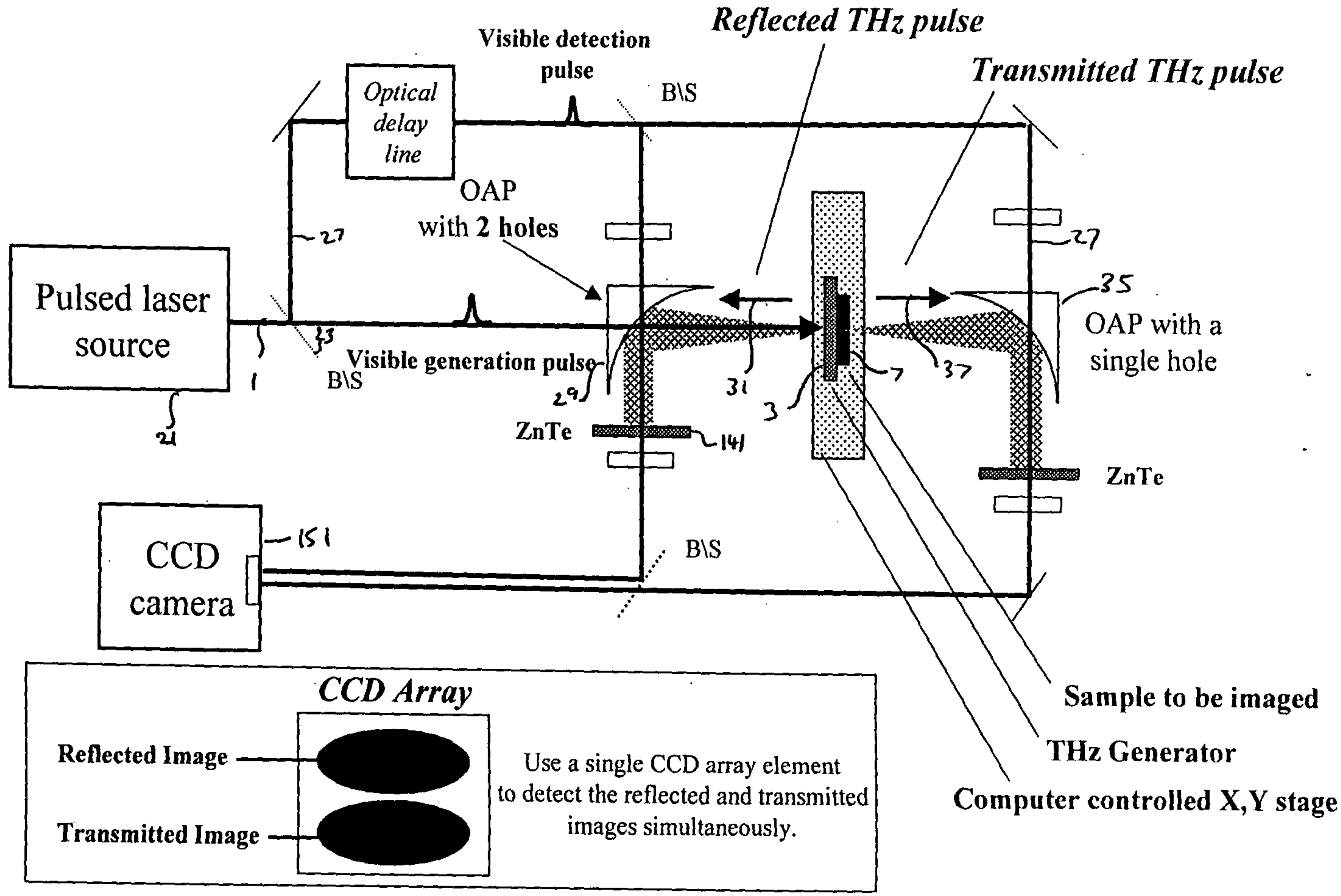
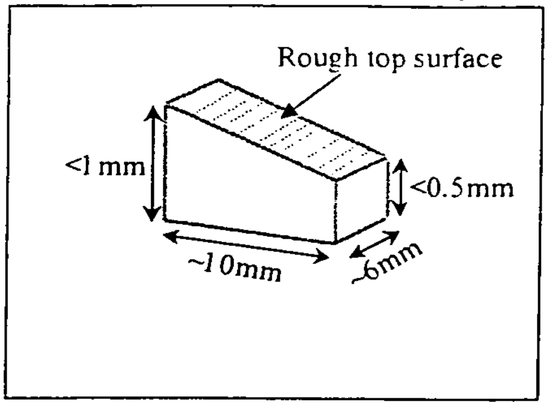
Figure 8: Full system - using CCD Camera detection - version 3

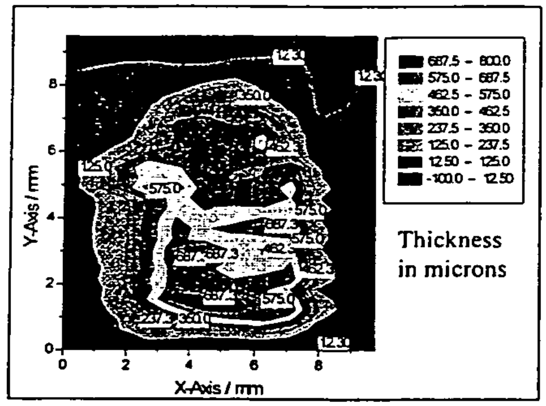


Version 3cc : June 99

(a) Schematic of wedged skin sample



(b) Contour plot of skin thickness



(c) 3D Plots of skin thickness at different perspectives

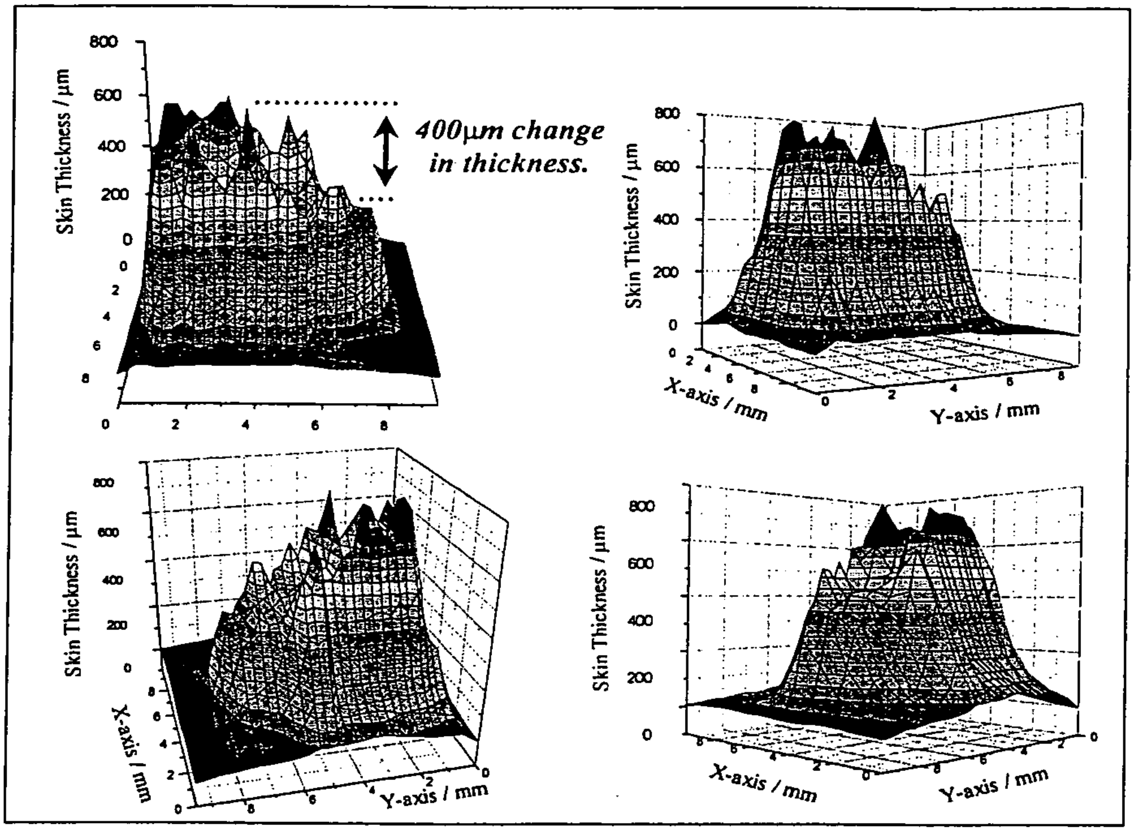
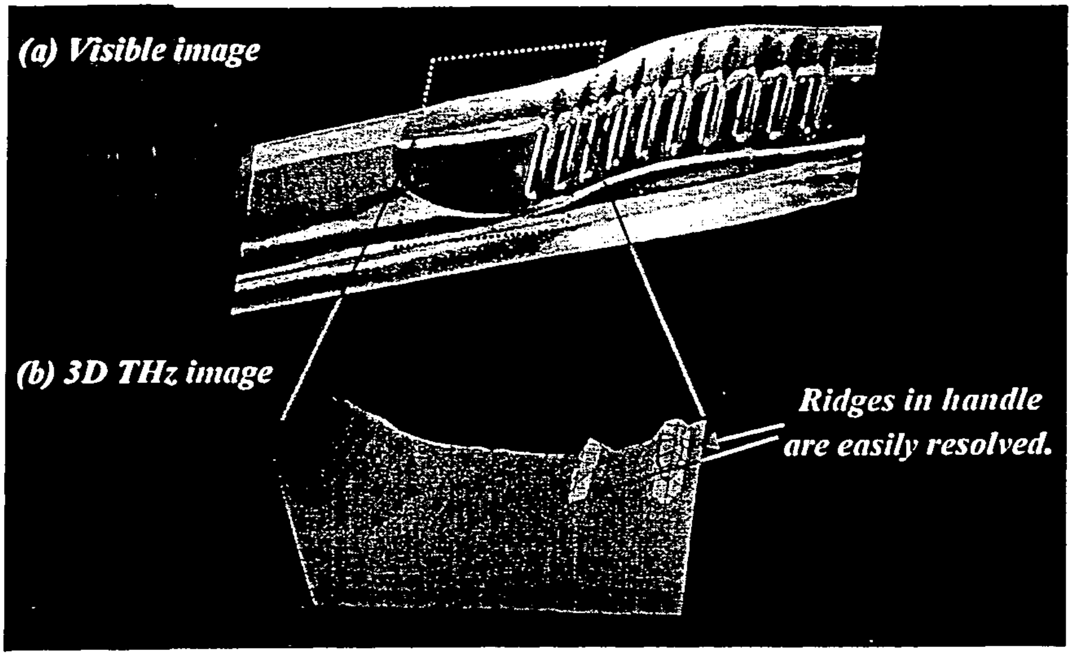
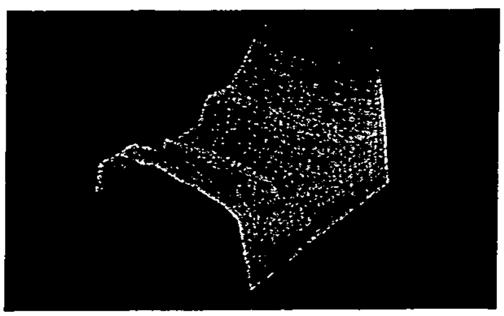
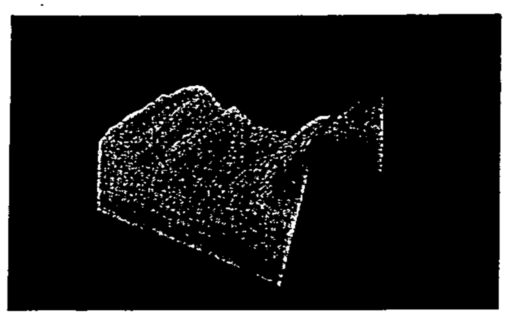


FIGURE 9

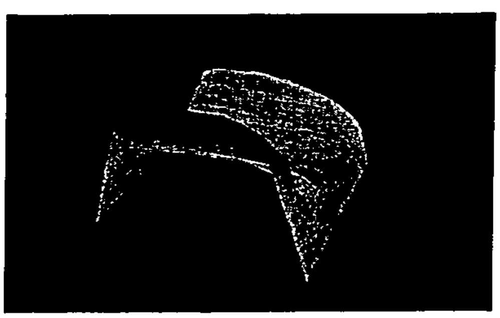




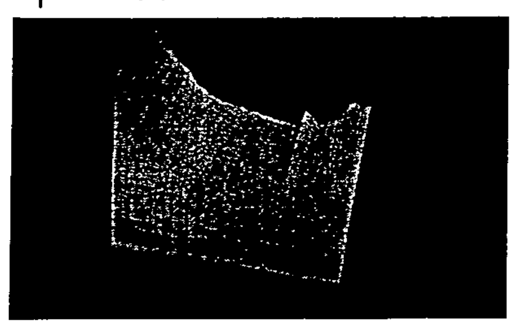
$\phi = 40^o$



$\phi = 160^o$



$\phi = 240^o$



$\phi = 320^o$

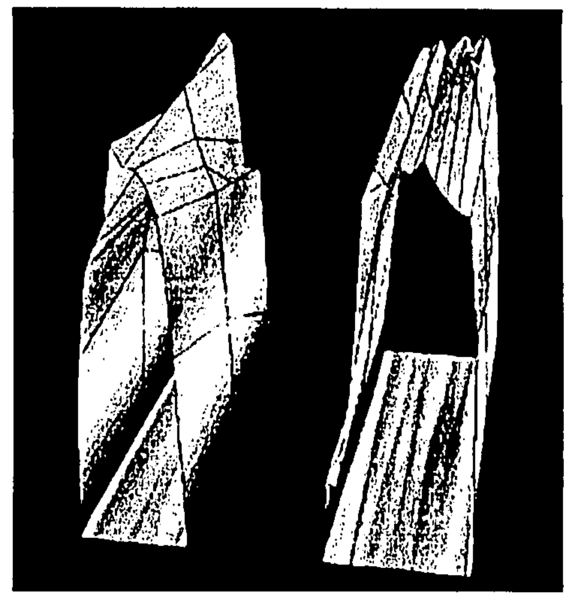
FIGURE 10

THz transmission through animal bone

Example of 2 bones - visible image

(a)

3D THz image through 2 bone sample



(b)

FIGURE 11

Medical Imaging using Terahertz light in a human tooth

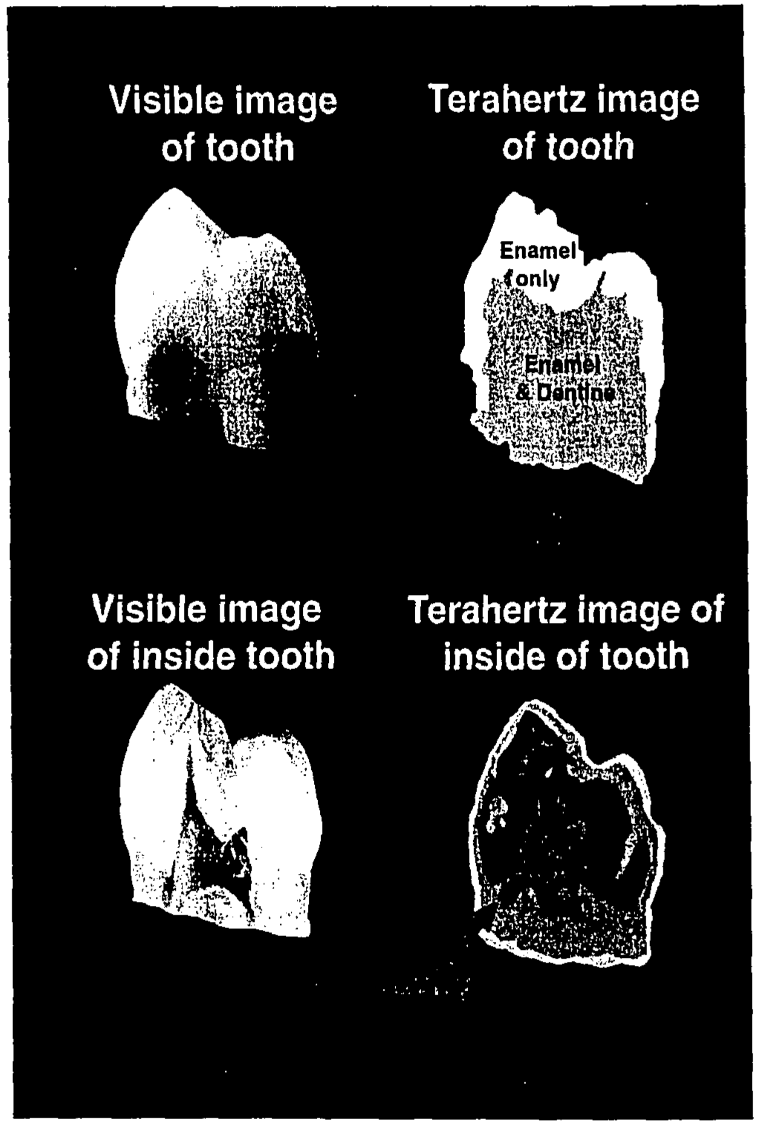


FIGURE R.

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4

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Dated 21 June 2000

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1/4

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The Patent Office

Request for grant of a Patent

29 JUN 1999

Form 1/77

Patents Act 1977

❶ Title of invention

1 Please give the title of the invention: Three Dimensional Imaging

❷ Applicant's details

☐ **First or only applicant**

2a If you are applying as a corporate body please give:

Corporate name: Toshiba Research Europe Limited

Country *(and State of incorporation, if appropriate)*: United Kingdom.

2b If you are applying as an individual or one of a partnership please give in full:

Surname

Forenames

2c **In all cases**, please give the following details:

Address:
Cambridge Research Laboratory,
260 Cambridge Science Park, Milton Road,
Cambridge, CB4 4WE, United Kingdom
United Kingdom.

UK postcode *(if applicable)*

Country

ADP number *(if known)* 7514136001

2d, 2e and 2f: If there are further applicants please provide details on a separate sheet of paper.

☐ **Second applicant *(if any)***

2d If you are applying as a corporate body please give:

Corporate name

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Agent's address 57-60 Lincoln's Inn Fields
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Agent's ADP number 18001

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eference number

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230P80799X

❺ Claiming an earlier application date

5 Are you claiming that this application be treated as having been filed on the date of filing of an earlier application?

Please mark correct box

Yes ☐ No ☒ ➡ ***go to 6***

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15(4) (Divisional) ☐ 8(3) ☐ 12(6) ☐ 37(4) ☐

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❻ If you are declaring priority from a PCT Application please enter 'PCT' as the country and enter the country code (for example, GB) as part of the application number.

Please give the date in all number format, for example, 31/05/90 for 31 May 1990.

6 If you are declaring priority from previous application(s), please give:

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GB	9913089.0	04/06/99

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- there is an [illegible]ventor who is not an applicant, **or**
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❼ Inv ntorship

7 Are you (the applicant or applicants) the sole inventor or the joint inventors?

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Yes ☐ No ☒ ➡ ***A Statement of Inventorship on Patents Form 7/77 will need to be filed (see Rule 15).***

❽ Please supply duplicates of claim(s), abstract, description and drawing(s).

❽ Checklist

8a Please fill in the number of sheets for each of the following types of document contained in this application.

Continuation sheets for this Patents Form 1/77 —

Claim(s)	5	Description	20
Abstract	1	Drawing(s) (INFORMAL)	9 +9

8b Which of the following documents also accompanies the application?

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Priority documents *(please state how many)*	—
Translation(s) of Priority documents *(please state how many)*	—
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Patents Form 10/77 – Request for Substantive Examination	—

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Three Dimensional Imaging

The present invention relates to the field of imaging samples with radiation in the infra-red (IR) and Terahertz frequency range. More specifically, the present invention relates to apparatus and methods for imaging samples in three dimensions using electromagnetic radiation in the higher Gigahertz (GHz) and the Terahertz (THz) frequency ranges. However, in this type of imaging technology, all such radiation is colloquially referred to as THz radiation, especially that in the range from 50GHz to 84THz.

Recently, there has been much interest in using THz radiation to look at a wide variety of samples using a range of methods. THz radiation has been used for both imaging samples and obtaining spectra. Recently, work by Mittleman *et al*, IEEE Journal of Selected Topics in Quantum Electronics, Vol. 2, No. 3, September 1996, page 679 to 692 illustrates the use of using THz radiation to image various objects such as a flame, a leaf, a moulded piece of plastic and semiconductors.

THz radiation penetrates most dry, non metallic and non polar objects like plastics, paper, cardboard and non polar organic substances. Therefore, THz radiation can be used instead of X-rays to look inside boxes, cases etc. THz has lower energy, non-ionising photons than X-rays, hence, the health risks of using THz radiation are expected to be vastly reduced compared to those using conventional X-rays.

A useful tool in almost all analysis techniques whether medical or otherwise is the ability to produce a three dimensional image of both the internal and external structure of a sample. The use of THz for producing the internal structure of a flat object (a floppy disc) has been described in EP 0 864 857. Here, the inventors

measured reflection of a beam of THz radiation to produce an image of the internal structure of the sample.

However, this method is not suitable for obtaining 3D images of objects where the front and back surfaces are curved. Most 3D objects have interfaces and/or external surfaces which are non-planar, i.e. have substantial radii of curvature. If a beam is reflected from a curved surface, it is reflected at an angle to the incident beam. The method of EP 0 864 857 does not show how to obtain an image when the radiation is reflected from a curved surface.

Also, partially absorbing objects give rise to weak reflections from buried layers resulting in long absorption lengths for certain reflected pulses. This limits the thickness of objects which can be accurately imaged in 3D using THz reflection imaging.

The present invention addresses the above problems in a first aspect provides a method of imaging a sample, the method comprising the steps of :

(a) irradiating the sample to be imaged with an irradiating beam of pulsed electro magnetic radiation with a plurality of frequencies in the range from 50 GHz to 84 THz,

(b) detecting both the radiation transmitted through the sample and the radiation reflected by the sample;

(c) generating an image of the sample from the radiation detected in step (b).

Collecting both the reflected and transmitted radiation technique allows a greater range of curved surfaces to be measured. Hence, the method of the present invention is capable of imaging a sample of virtually any shape. The collection of both

the transmitted and reflected radiation allows a three dimensional image and/or a compositional image of the sample to be obtained.

Radiation transmitted through the sample is primarily used to determine the sample shape and the composition. Radiation which is reflected from the sample is primarily used to measure the positions of dielectric surfaces within the sample in addition to giving shape information. This technique allows the curvature of both internal and external surfaces to be measured. Thus, using both reflected and transmitted radiation is an extremely powerful tool to determine the three dimensional compositional structure of the object.

In addition to collecting both transmission and reflection data, it is preferable if the resolution of the system is not limited by the diffraction limit. Therefore, it is preferable if the beam which irradiates the sample has a beam diameter which is smaller than the smallest wavelength of radiation in the pulse of electromagnetic radiation.

To obtain an image of the whole sample, the sample is preferably subdivided into a 2 dimensional pixel array. The radiation which is either reflected by or transmitted through each pixel is detected. The image is then generated pixel by pixel.

Preferably, the sample which is to be imaged is placed on a motorised stage, which can be stepped in the both the x and y directions. The image of the whole area of the sample can then be built up pixel by pixel.

Due to the beam diameter being smaller than the wavelength of the radiation, the present invention utilises near-field techniques. Hence, the spatial resolution is not determined by the focused spot size of the THz beam.

The beam of pulsed radiation which is used to irradiate the sample is preferably generated by an emitter which has non-linear optical properties. The material of the emitter is preferably chosen such that when the emitter is irradiated with radiation with

a predetermined input frequency or frequencies, the emitter emits a beam with the desired output frequency or frequencies i.e. a frequency or frequencies in the range from 50 GHz to 84 THz. The frequency of the emitted beam is determined by both the frequency or frequencies of the input radiation and the non-linear properties of the emitter itself.

The emitter can be a semiconductor crystal with non-linear optical properties type which allow visible pulses of light (i.e. pulses with wavelengths in the range from 0.3 μm to 1.5 μm) to be converted to pulses with a wavelength in the range from 50 GHz to 84 THz. The emitter may be chosen from a wide range of materials, for example, $LiIO_3$, $NH_4H_2PO_4$, ADP, KH_2PO_4, KH_2ASO_4, Quartz, $AlPO_4$, ZnO, CdS, GaP, GaAs, $BaTiO_3$, $LiTaO_3$, $LiNbO_3$, Te, Se, ZnTe, ZnSe, $Ba_2NaNb_5O_{15}$, $AgAsS_3$, proustite, CdSe, $CdGeAs_2$, $AgGaSe_2$, $AgSbS_3$, ZnS, DAST (4-N-methylstilbazolium) or Si.

In this case of an emitter which has non-linear optical properties, to keep the input beam in phase with the emitted beam (THz beam), the emitter preferably comprises phase matching means. The phase matching means can be of the type for enhancing the phase matching between at least two different frequency signals propagating in the emitter in response to illumination by at least one incident beam of radiation, the phase matching means having a spatial rotation in its refractive index along a component of the incident radiation beam.

Preferably, the diameter of the beam which irradiates the sample is determined by the diameter of the visible or near-infrared beam which irradiates the emitter. In this situation, there is no need to have extra active optical components between the sample and the emitter to focus the beam. However, in such an arrangement, the sample needs to be positioned close to the emitter. The sample may be mounted directly onto the emitter. Alternatively, the sample may be mounted in very close proximity to the semiconductor emitter. For example, between 10 and 500 μm. Also, the sample may

be mounted on a passive optical component which is invisible to THz radiation i.e. a window. The window does not serve to focus the beam.

It may be preferable to separate the emitter and the sample, if the emitter comprises a toxic material, for example, ZnTe.

In the method of the present invention, both transmitted and reflected radiation pulses are measured. When an emitter of the type described above is used, the reflected THz passes must pass back through the emitter (without significant losses) before they are collected as reflected THz for analysis. Therefore, preferably, the emitter is transparent to THz radiation or at least to the radiation of the irradiating beam. Semiconductors with a low carrier doping concentration are useful for this aspect.

Also, in order to permit a range of sample sizes and radii of surface or interface curvatures to be measured, the emitter must also be sufficiently large to allow all of the reflected beams to pass back through the emitter. If the emitter is too small, or if the imaging takes place too close to the edge of the emitter, some of the reflections may be blocked by the mount of the emitter. To allow a smaller crystal to be used, it is preferable if just the sample moves in order to image the area of the sample. As the sample moves relative to both the emitter and the input beam of the emitter, a smaller emitter can be used.

To further reduce the size of the emitter is mounted on a "THz window". The window material could be for example polyethylene, polythene, high-resistivity silicon, Z-quartz or TPX (poly-4-methylpentene-1), it must be at least substantially transparent to the irradiating beam. The window would preferably be thin, for example, between 50 and 300 microns. This is to ensure that the THz beam diameter is still smaller than the shortest wavelength component when the THz beam reaches the sample. The size of the window is large enough to allow all of the reflected beams to be collected with negligible loss. As the emitter is provided on the window which is substantially transparent to THz, the THz can pass through the mount for the emitter.

Also, using conventional coherent THz detection methods, for example, electro-optic sampling and photoconductive detection, the THz beam must be focused to a point and thus information is lost about the path the different THz beams take following reflection. This problem can be addressed by using a CCD camera. Therefore, it is preferable if a CCD camera is used in the detection the reflected THz beams. This detection method allows reflection techniques to map out the shape of curved surfaces, also, it would be possible to map out differences in shape between internal and external dielectric surfaces.

It should be noted that the CCD camera would not be used to detect the THz directly, instead the THz would be converted to a visible or near IR radiation an electro-optical component, the near IR visible radiation would then be collected by the CCD. Preferably, this conversion to IR or visible radiation would be achieved by passing a polarised reference beam with the THz beam through a material which supports the AC pockets effect. The light emitted by the material is then passed through a polariser to the CCD. Only light which has had its polarisation rotated by the THz signal will be transmitted be the polariser into CCD.

Also, when collecting the output light using an off axis parabolic mirror, there is a slight time delay due to the different optical path lengths between the centre and the edge of the mirror. Consequently, the different path lengths of the reflected beams cause the pulses to arrive at different times at the detector. This causes a problem, because it is not easy (if at all possible) to distinguish between a time-shift of a pulse due to the position of an internal dielectric layer and a time shift which is a combination between a reflection from the sample and a different path length due to one of the optical mirrors. This problem can also be addressed by the use of a CCD camera as a detector. A CCD camera can be used to image a 2D region containing all the reflected THz beams, both the temporal and spatial shift if the THz can be measured. In other words, more exact information about the sample can be gained by using a CCD camera.

The CCD technique can be used to collect radiation which is both transmitted and reflected from the sample. As in many situations, the transmitted beam may also be transmitted off axis.

In the method of the present invention, data can be derived by using the time-of-flight method. As the enters the sample, its velocity changes due to variations in the refractive index of the sample. Thus, by measuring the time of flight of the pulse through the sample, an image of the sample shape can be obtained using transmission.

Using the frequency domain analysis techniques of UK application no 9940166.7, the composition of the structure can be determined. In this application, a single frequency from the plurality of transmitted or reflected plurality of frequencies is used to generate the image. In some cases, a narrow range of frequencies or a selection of specific frequencies or frequency ranges is studied. A selected frequency range is taken to be a frequency range typically less than a third of the total range of the passed electromagnetic radiation used to irradiate the sample. More preferably, the selected frequency range is less than 10% of the total frequency range of the passed electromagnetic radiation used to irradiate the sample.

For example, water is a strong absorber of THz radiation. There are "windows" in the water absorption spectra from 50 GHz to 500 GHz, from 30 THz to 45 THz and from 57 THz to 84 THz. If the sample is irradiated with a range of frequencies from 50 GHz to 84 THz, it may be preferable to generate the image using one or more of the following selected frequency ranges: 50 GHz to 500 GHz, 30 THz to 45 THz and 57 THz to 84 THz. The image may be generated by integrating over the selected frequency range.

Thus, by analysing the transmitted information as above, an image can be created by a single frequency or a selected frequency range. Also, a plurality of images may be derived from a plurality of frequencies or a single image may be derived from

two or more distinct frequencies. This is a very powerful analysis and allows variation in the composition of the material to be determined.

The image or images may be generated in a number of ways. For example, a sequence of images may be generated from a plurality of different frequencies.

In general, the present invention will be performed using imaging apparatus which is configured to detect temporal data at each pixel. Preferably, the data is Fourier transformed to give the complex THz electric field in the frequency domain $E(\omega)$.

The image can be obtained in a number of ways from the complex THz electric field $E(\omega)$, e.g.:

(i) The power spectrum $P_{sample}(\omega)$ of the sample and the power spectrum $P_{ref}(\omega)$ of the reference signal may be calculated. The image could then be generated by plotting the difference between the two Power spectrums for a given frequency for each pixel at a selected frequency over integrated over a selected frequency range.

(ii) The power spectrum P_{sample} of the sample and the reference power spectrum P_{ref} may be divided to give the transmittance. The transmittance may then be plotted for each pixel at a selected frequency over integrated over a selected frequency range.

(iii) The frequency dependent absorption coefficient $\alpha(\omega)$ may be calculated from the complex electric field $E(\omega)$ and plotted for each pixel at a selected frequency over integrated over a selected frequency range.

(iv) The frequency dependent refractive index $\eta(\omega)$ may also be calculated from the complex electric field and plotted for each pixel at a selected frequency over integrated over a selected frequency range.

The detected temporal electric field contains both phase and amplitude information which give a complete description of the complex dielectric constant of the medium in the beam path. The sample to be characterised is inserted into the beam and the shape of the pulses that have propagated through the sample or have been reflected from the sample are compared with the reference temporal profile acquired without the sample. The ratio of the complex electric field $E(\omega)$ and the reference signal $E_{ref}(\omega)$ is calculated to give the complex response function of the sample, $S(\omega)$. In the most simple case, the complex response function is given by:

$$S(\omega) = \frac{E(\omega)}{E_{ref}(\omega)} \propto \exp\left(\frac{i\omega d}{c}(\eta(\omega) - 1)\right)\exp(-\alpha(\omega)d) \qquad (1)$$

where d is the sample thickness, c is the velocity of light in vacuum, η is the refractive index and α is the absorption coefficient. The experimental absorption coefficient $\alpha(\omega)$ and the refractive index $\eta(\omega)$ may then be easily extracted from the magnitude $M(\omega)$ and the phase $\phi(\omega)$ of $S(\omega)$, respectively, according to

$$\alpha(\omega) = -\frac{1}{d}\ln(M(\omega)) \qquad (2)$$

$$\eta(\omega) = 1 + \left(\frac{c}{\omega d}\right)\phi(\omega) \qquad (3)$$

Additional terms may be included in equations (1) to (3) to account for reflections at dielectric interfaces of a sample, thus allowing accurate analysis of multilayered samples.

These parameters are simply related to the complex dielectric function $\varepsilon(\omega)$ of the sample

$$\varepsilon(\omega) = (\eta(\omega) + ik(\omega))^2 = (\eta(\omega) + i\alpha(\omega)c/2\omega)^2 \qquad (4)$$

The data derived as discussed in (i) to (iv) above, may be directly plotted either as a colour or a grey scale image where the colour or shade of grey of each pixel represents a given magnitude.

Instead of a single frequency, a selected frequency range could be chosen and the result and data of (i) to (iv) integrated over that range. The integrated data could then be plotted.

It may also be preferred to subdivide the magnitude of the data process in accordance with any of (i) to (iv) above into various bands. For example, all data below a certain value could be assigned the value 0, all data in the next magnitude range could be assigned the value 1, etc. These ranges may have equal widths in magnitude or they may have different widths. Different widths may be preferable to enhance contrast e.g. to emphasise contrast in regions of the sample where there is little variation in the sample absorption of THz.

Preferably, the present invention uses two or more frequencies. The data from say two frequencies is processed in accordance with any of (i) to (iv) above. The data is then banded as described for a single frequency above.

The data may be split into two hands, one assigned the value "0" and the other "1". The data from both frequencies can then be added together using a rule such as a Boolean algebraic expression e.g. AND, OR, NOT, NAND, XOR, etc.

Of course, the present invention also allows images to be compared from two different frequencies. This may be particularly useful to identify a substance where the absorption to THz changes over a certain frequency range.

Thus, complex images can be produced. This system is particularly useful in the detection of breast cancer where both spatial information and compositional

information concerning the 3D structure of the breast can be derived. Also, the present invention can be used to image teeth and bone.

The method of the present invention allows the internal composition, shape and the position of the internal surfaces to be determined. Hence, a three dimensional image of the sample can be produced from the methods of the three aspects of the present invention. In a second aspect, the present invention provides an apparatus comprising:

a) means for irradiating a sample to be imaged with an irradiating beam of pulsed electromagnetic radiation with a plurality of frequencies in the range from 50GHz to 84THz;

b) means for detecting radiation which is both transmitted through and reflected from the sample; and

c) means for generating an image of the sample from radiation detected in step (b).

For the reasons described above, it is preferable if the imaging is performed in the near-field regime. Therefore, it is preferable if the means for radiating a sample comprises an emitter for emitting a beam of radiation with a plurality of frequencies in the range from 50 GHz to 84 THz, the emitter having optical non linear properties, such that when the emitter is irradiated with an input beam with a frequency in the visible or near infra-red frequency ranges, a beam is emitted with frequencies in the range from 50 GHz to 84 THz. Preferably, the input beam of pulsed radiation has a diameter which is smaller than that of the smallest wavelength of the emitted beam.

To image the sample, the sample should be stepped pixel by pixel in two orthogonal directions. Therefore, it is preferable that the apparatus further comprises a

motorised stage configured so that it can be stepped pixel by pixel into two orthogonal directions.

The sample itself can be mounted on the motorised stage. Alternatively, both the sample and the emitter can be mounted on the motorised stage.

The present invention will now be described with reference to the following preferred non-limiting embodiments, shown in the following drawings in which:

Figure 1 shows a schematic near-field transmission and reflection imaging system according to an embodiment of the present invention;

Figure 2 shows the system of Figure 1 with a source and detectors for both the transmitted and reflected radiation;

Figure 3 shows a variation on the imaging system of Figure 2;

Figure 4 shows the imaging system of Figure 2 with details of the detectors;

Figure 5 shows the imaging system of Figure 2 with details of the detectors;

Figure 6 shows the imaging system of Figure 2 with details of the detectors;

Figure 7 shows a variation on the imaging system of Figure 6;

Figure 8 shows a variation on the imaging system of Figures 6 and 7.

Figures 9a, 9b and 9c show three variations on the method of mounting the sample to be imaged.

Figure 1 is a schematic of a near-field transmission and reflection imaging system. A focused visible beam (which has a wavelength in the visible electro-magnetic region i.e. typically between 0.3 μm to 1.5 μm) 1 is focused onto a THz emitter 3. The THz generation crystal is a crystal with non-linear properties which will emit radiation in the THz regime (50GHz to 84THz) when irradiated by visible light. The THz pulse 5, is emitted from the THz generation crystal 3. The actual frequency of the emitted beam is determined by the frequency of the input radiation and the physical properties of the emitter itself. An emitted beam with the desired frequency range can be obtained by appropriate selection of the emitter material and the frequency of the input radiation.

The diameter of the input which impinges on the THz generation crystal, is smaller than that of the smallest wavelength which will be generated in the THz pulse from the emitter 3. The sample 7, is directly mounted onto the emitter 3. Therefore, the sample is imaged with a beam of THz radiation which has a beam diameter which is less than that of the smallest wavelength of the THz light. Thus, the resolution of the image obtained from the sample will not be limited by the diffraction limit.

Some of the THz pulse will be transmitted through the sample 7. The transmitted THz is denoted by reference numeral 9. THz pulses will also be reflected from the sample 10. In this specific example, the first reflection of the THz pulse 5 occurs at the interface 11 between the sample 7 and the emitter 3. A second dielectric interface 13 within the sample 7 causes reflection R_2 which is the second reflected THz pulse. This pulse will be reflected at a time $\Delta\tau_1$ the third reflection R_3 occurs as the THz pulse leaves the sample 7. By collecting both the reflected and transmitted pulses, considerable detail about sample 7 can be determined.

The reflected THz pulses 10 are collected by off axis parabolic mirror 12. The passes are then reflected into a detector (not shown). The off axis parabolic mirror 12 has a hole 14 for transmitting the focused visible beam 1 from the source (not shown) to the emitter 3.

Figure 2 shows a complete system. For convenience, like numerals denote like components on the previous and remaining figures. Pulse laser source 21 provides the beam of visible light 1. The beam of light 1 impinges on beam splitter 23. The beam splitter may be a half silvered mirror or the like. Beam splitter 23 passes a part of the visible pulse 25 towards the emitter 3 and a second part of the visible pulse 27 is reflected towards the detection mechanism. This beam 27 will eventually be used as a reference beam in the detection mechanism. Initially looking at the visible beam 25 which is used for generating the THz beam, this is first passed through an off axis parabolic mirror 29. The off axis parabolic mirror 29 has a hole to allow transmission of the visible pulse therethrough. The pulse is then directed onto the emitter 3 as shown in Figure 1.

As explained above in relation to Figure 1, the THz pulse 5 is reflected off the external surfaces and dielectric internal surfaces of the sample 7. This reflected pulse 31 is then collected by off axis parabolic mirror 29 (this is the same mirror through which the visible pulse 25 passes). The mirror 29 reflects the pulse into THz detector 33 which is used to produce the image. A second off axis parabolic mirror 35 is used to collect the transmitted THz pulse 37 from the sample 7. The off axis parabolic mirror 35 directs the transmitted pulse onwards transmitted pulse THz detector 39.

Visible pulse 27 is directed via mirrors, 43, 45 and 47 into THz detectors 33 and 39. An optical delay line 49 is provided to synchronise the visible pulse 27 with the collected reflected and transmitted THz radiation. As the reflected and transmitted THz radiation passes through the sample, the pulse is delayed, the optical delay line compensates for this effect.

Figure 3 shows a variation of the imaging system of Figure 2. Figure 3, is very similar to Figure 2. However, here, the visible beam 25 impinges on a dichoric beam splitter 51. The beam splitter is ideally 100% reflective to the visible light but 100% transparent to the reflected THz beam. In this arrangement, the dichoric mirror 51

reflects the beam onto the off axis parabolic mirror 29. The off axis parabolic mirror then directs the visible beam onto the emitter 3. As the visible beam 25 is being reflected from the off axis parabolic mirror, the off axis parabolic mirror 29 can be used to focus the beam to a small diameter (about 100 microns) on the generation crystal 3.

The reflected THz pulse 31 is collected in the same manner as described for Figures 1 and 2, the reflected pulse as collected by off axis parabolic mirror 29. The off axis parabolic mirror 29 directs the reflected pulse 31 onto dichoric mirror 51. The dichoric mirror is transparent to THz therefore it transmits the pulse 31 into THz detector 33.

The collection of the transmitted radiation 37 and the direction of the reference beam 27 into detectors 33 and 39 is identical to that described in Figure 2.

Figure 4 shows a full detection system using electro-optical detection. The system is largely identical to that of Figure 2. However here, the THz detectors 33 and 39 are shown in more detail. Detection systems 33 and 39 are identical. Therefore, for simplicity only detection system 33 will be described.

In the detector 33 the THz beam carrying the reflected sample information 101 and a visible light beam 27 are combined using an off axis parabolic mirror 103. The off axis parabolic mirror 103 has a hole for the transmission of the visible beam 27 therethrough. Both the visible beam 27 and the reflected beam 101 are then directed onto a THz detection crystal 105. The visible light beam 27 acts as a reference beam which is incident on the detection crystal 105. Each of the axes has distinct refractive indices n_0 and n_e along the ordinary and extraordinary axis of crystal 105 respectively. In the absence of a second THz radiation beam 101, the linearly polarised reference beam 27 passes through the detection crystal 105 with negligible change to its polarisation.

The applicant wishes to clarify that although the angle through which the polarisation is rotated by is negligible, the linearly polarised beam can become slightly elliptical. This effect is compensated for by a variable retardation wave plate, eg. a quarter wave plate 107. The emitted beam is converted into circularly polarised light using the quarter wave plate 107. This is then split into two linearly polarised beam by a beam splitter such as a Wollaston prism 109 which directs the two orthogonal components of the polarised beam onto a balanced photodiode assembly 111. The balanced photodiode signal is adjusted using wave plate 107 such that the difference in outputs between the two diodes is zero.

However, if the detector 107 also detects a secondary beam 101 (in this case a beam with a frequency in the THz range) as well as the reference beam, the angle through which the polarisation is rotated is not negligible. This is because the THz electric field modifies the refractive index of the visible (fundamental) radiation along one of the axes n_e, n_o. This results in the visible field after the detector 105 being elliptical and hence the polarisation component separated by the prism 109 are not equal. The difference in the signal between the diode outputs gives a detection signal.

The reference beam 27 and the THz beam 101 should stay in phase as they pass through the crystal 105. Otherwise, the polarisation rotation is obscured. Therefore, the detection crystal 105 has phase matching means to produce a clear signal.

The optical delay is introduced by cube mirror 121 and plane mirror 123. Cube mirror 121 moves in and out to vary the length of the optical path and of the reference beam 27.

Figure 5 shows a variation on the system of Figure 4. Here, photoconductive detection by photoconductive THz detectors 131 and 133 are used to detect the transmitted and reflected THz beam.

The system shown in Figures 4 and 5, the systems have a single optical delay line (which is achieved by cube mirror 121 and plane mirror) that services both detection elements. Alternatively, a separate delay line for each detection element could be used. This may be necessary when very thick objects are imaged. Here, the transmitted THz pulse would experience a longer delay than the pulse reflected from the front surface. Hence, a single optical delay may not be suitable.

The off axis parabolic mirrors 29, 35 need to be carefully aligned to ensure efficient collection of both the transmitted 37 and reflected 31 THz beams.

If a THz beam is incident on a curved surface, i.e. one with a surface normal not parallel to the direction of the THz beam, the THz beam will not be reflected along the same axis. Instead, it will be reflected at an angle which increases with the surface curvature.

In the two above THz detection methods, the THz is focused to a point for detection, thus information about the path the different THz beams take following reflection can be lost.

Also, when collecting the output using an off axis parabolic mirror, there is a slight time delay due to the different optical path lengths between the centre and the fringe and the mirror. Consequently, the different path lengths reflected beams would cause the pulses to arrive at different times at the detector. Using the detection methods of Figures 4 and 5, the beams are focused to a single point. This causes a problem as it is difficult (if not impossible) to discriminate between a time shift due to the opposition of dielectric layer and a time shift that is a combination of the dielectric position and a different paths length on the mirror. The effects of different paths to the mirror are greatest when the surfaces/interfaces are sharply curved. However, if using a CCD camera both the temporal and spatial shift of the THz beam can be measured and this allows the exact curvature of the sample pixel by pixel to be determined.

Figure 6 shows a similar system to that of Figures 4 and 5. The difference is that the detection mechanism of Figure 6 uses a CCD.

The reference beam 27 is reflected off mirror 47 and is polarised by passing the beam through polariser 142. The polarised reference beam 27 is then combined with the reflected radiation 101 using beam splitter 102. The beam splitter is transparent to THz radiation and hence THz radiation is transmitted through beam splitter 102. However, it is not transparent to visible light and hence the reflected polarised reference beam 27 is combined with the THz beam. The reflected THz beam 101 and the reference beam 27 are directed toward detector crystal 141. This detection mechanism is based on AC Pockles effect and the polarisation of reference beam 27 is rotated by the presence of reflected THz beam 101. The emergent beam 139 is then passed through polariser 140. Polarisers 140 and 142 are crossed relative to each other. Therefore, if no THz beam is present, the polarisation of beam 27 is not rotated and hence the beam is blocked by polariser 140. However, if the beam is rotated, polariser 140 will transmit at least a part of the transmitted beam 139. The output of output 140 is then directed to CCD camera 143. Hence, CCD camera 143 is used to detect the presence of THz radiation and it also gives the spatial dependence of the reflected THz beam via the spatial variations detected by the CCD.

Figure 7 shows a variation on the system of Figure 6. The system of Figure 7 is more compact than that of Figure 6. The visible input beam 23 is transmitted onto the emitter 3 through a hole in off axis parabolic mirror 29 in the same manner as described with reference to Figure 1. Off axis parabolic mirror 29 is used to collect the reflected radiation and directed into detector 33. Similarly, the transmitted radiation is collected by off axis parabolic mirror 35 and is directed into detector 39.

The main difference between this system and the system of Figure 6 is the way in which the reference beam is combined with the reflected and transmitted THz beams. The reference beam 27 is fed through an optical delay line 49 as previously described. The part of the beam 27a which is to be used for the reflected THz signal is passed

through a first crossed polariser 201a. This polarised reference beam is then passed through a second hole in off axis parabolic mirror 29 such that the reflected THz pass 31 and the polarised reference signal 27a are both directed into the detector 33. In the same way as described with reference to Figure 6, the THz beam 31 causes rotation of the polarisation of the reference beam 27a. A second polariser 203a blocks the path of any radiation which has not been rotated. 201a and 203a are crossed polarisers. The beam is then fed into CCD camera 143.

The reference beam for the transmitted beam is split off as beam 27b. This beam is then passed through polariser 201b to obtain a polarised reference beam. The beam 27b is then passed through a hole in off axis parabolic mirror 35 to combine the transmitted THz radiation 37 with the reference beam 27b. The presence of the transmitted THz is then detected via rotation of the polarisation of the reference beam 27b as described previously. The emergent beam is then fed into polariser 203b. Polariser 203b is crossed with polariser 201b such that polariser 203b blocks any radiation which has not had its polarisation vector rotated.

Figure 8 shows a very similar system to that of Figure 7. Here, though instead of two CCD cameras 143 and 145 a single CCD camera 151 is used to detect both the transmitted and the reflected radiation. Specifically, the beam which is transmitted by second cross polariser 203a is directed into CCD camera 151. Also, the beam which is transmitted by second crossed polariser 203b (transmitted radiation) is also directed into CCD camera 151. The use of the single CCD array element means that reflected and transmitted images are detected simultaneously.

In Figures 1 to 8, the sample is shown actually mounted on the emitter. This arrangement is specifically shown in Figure 9a. To obtain a full image of an area of the sample, the sample is stepped relative to the THz beam in both the x and y directions, pixel by pixel. This can be done by mounting the sample on the emitter and moving both the emitter and the sample together using the motorised stage.

In the imaging system, both reflected and transmitted radiation must be collected. Therefore, the reflected THz pulses have to be passed back through the emitter crystal before reaching the off axis parabolic mirror (reference numeral 29 in Figures 1 to 8). In other words, the emitter acts as a window for the reflected THz. Also, to allow a large range of sample sizes and surface curvatures to be measured, the emitter must also be sufficiently large to allow all of the reflected beams to pass back through it.

Figure 9b shows an arrangement which allows a smaller emitter to be used. In this arrangement, the sample is mounted in close proximity to the emitter (for example, between 10 and 500 μm and only the sample is moved in the x-y planes). In other words, the sample is moved relative to the emitter. To ensure high spatial resolution (i.e. in the near field region), the sample must be kept close to the emitter surface. Also, the sample may be mounted on a thin window which is in turn mounted about 10 to 100 μm from the surface of the emitter 3. In this case, the emitter still needs to be large enough to permit all the reflected pulses from the sample to reach the off axis parabolic mirror 29. The required emitter size in the arrangement of 9b is smaller than that of 9a as in 9a, the emitter needs to be big enough to catch all reflections from the sample. In the arrangement in 9b, the emitter just needs to be big enough to catch all reflections from the small part of the sample being imaged.

In Figure 9c, the emitter is mounted on a THz window 4. As the mount for the emitter transmits THz, the emitter can be made even smaller as there is no requirement now for all of the reflected THz pulses to pass back through the emitter. The emitter just needs to be big enough to produce the THz beam. Again, the sample is mounted in close proximity to the emitter as opposed to onto the emitter. In this arrangement, only the sample needs to be moved. Therefore, the emitter only needs to be a few millimetres square in area (for example, less than 23mm by 25mm). The window 4 is thin (between 50 μm and 300 μm) to ensure that the THz beam diameter is still smaller than the shortest wavelength component when it reaches the sample.

CLAIMS:

1. A method of imaging a sample, the method comprising the steps of :

(a) irradiating the sample to be imaged with an irradiating beam of pulsed electro magnetic radiation with a plurality of frequencies in the range from 50 GHz to 84 THz,

(b) detecting both the radiation transmitted through the sample and the radiation reflected by the sample;

(c) generating an image of the sample from the radiation detected in step (b).

2. A method according to claim 1, wherein the irradiating beam has a beam diameter smaller than that of the smallest wavelength of the radiation of the beam.

3. A method according to any preceding claim, wherein the irradiating beam is emitted by an emitter, the emitter being irradiated with at least one input beam of radiation with frequencies in the visible or near infra red frequency range, the emitter being a material with non-linear optical properties

4. A method according to claim 3, wherein the input beam has a beam diameter which is smaller than the smallest wavelength of the beam of pulsed radiation of step (a).

5. A method according to either of claims 3 or 4, wherein the emitter is a semiconductor.

6. A method according to any of claims 1 to 4, wherein the material with non-linear optical properties is chosen from the group of $LiIO_3$, $NH_4H_2PO_4$, ADP, KH_2PO_4,

KH_2ASO_4, Quartz, $AlPO_4$, ZnO, CdS, GaP, GaAs, $BaTiO_3$, $LiTaO_3$, $LiNbO_3$, Te, Se, ZnTe, ZnSe, $Ba_2NaNb_5O_{15}$, $AgAsS_3$, proustite, CdSe, $CdGeAs_2$, $AgGaSe_2$, $AgSbS_3$, ZnS, DAST (4-N-methylstilbazolium) or Si.

7. A method according to any of claims 3 to 6, where the sample is mounted such that there are no active optical components between the sample and the emitter.

8. A method according to any of claims 3 to 7, wherein the emitter is configured to hold the sample.

9. A method according to any of claims 3 to 8, wherein the sample is positioned with a separation from 10 μm to 500 μm from the emitter.

10. A method according to any of claims 3 to 9, wherein the emitter is of a size such that radiation reflected from the sample can pass back through the emitter.

11. A method according to any of claims 3 to 10, wherein the emitter is substantially transparent to the irradiating beam.

12. A method according to any of claims 3 to 11, wherein the emitter is mounted on a material which is transparent to the irradiating beam.

13. A method according to any preceding claim, wherein the sample is mounted on a material which is transparent to the irradiating beam.

14. A method according to any preceding claim, wherein in step (b), an area of the sample which is to be imaged is subdivided into a two-dimensional array of pixels, and radiation is detected from each pixel.

15. A method according to claim 14, wherein the sample is moved, such that the transmitted and reflected radiation can be detected pixel by pixel.

16. A method according to claim 15 when dependent on claim 3, wherein both the sample and the emitter are moved, such that the reflected and transmitted radiation can be detected pixel by pixel.

17. A method according to any preceding claim, wherein a CCD camera is used to detect the radiation reflected from the sample.

18. A method according to any preceding claim, wherein a CCD camera is used to detect the radiation transmitted through the sample.

19. A method according to any preceding claim, wherein a three dimensional image is generated in step (c).

20. A method according to any preceding claim wherein a compositional image is generated in step (c).

21. An apparatus for imaging a sample, the apparatus comprising:-

a) means for irradiating a sample to be imaged with an irradiating beam of pulsed electromagnetic radiation with a plurality of frequencies in the range from 50GHz to 84THz;

b) means for detecting radiation which is both transmitted through and reflected from the sample; and

c) means for generating an image of the sample from radiation detected in step (b).

22. An apparatus according to claim 21, wherein the means for irradiating a sample, comprises an emitter for emitting the irradiating beam, the emitter having optical non-

linear properties, such that when the emitter is irradiated with an input beam with a frequency in the visible or near infra-red frequency ranges, a beam is emitted with frequencies in the range from 50GHz to 84THz.

23. An apparatus according to claim 22, wherein the input beam of pulsed radiation has a diameter which is smaller than that of the smallest wavelength of the irradiating beam.

24. An apparatus according to claim 21, wherein the apparatus further comprises a motorised stage, configured so that it can be stepped pixel by pixel in two orthogonal directions.

25. An apparatus according to claim 24, wherein the sample is mounted on the motorised stage.

26. An apparatus according to claim 25 when dependent on claim 22, wherein both the sample and the emitter are mounted on the motorised stage.

27. An apparatus according to claim 25, when dependent on claim 22, wherein the emitter is mounted on a material which is transparent to the irradiating beam.

28. An apparatus according to claim 27, wherein the area of the emitter which faces the sample is 25mm x 25mm or less.

29. An apparatus according to an of claims 27 or 28 when dependent on claim 25, wherein the sample is moveable relative to the emitter.

30. An apparatus according to any of claims 21 to 29, wherein the means for detecting the radiation comprises a CCD camera for detecting the reflected radiation.

31. An apparatus according to any of claims 21 to 30, wherein the means for detecting the radiation comprises a CCD camera for detecting the transmitted radiation.

32. An apparatus according to any of claims 21 to 31, wherein the means for generating an image of the sample comprises means for generating a three dimensional image of the sample.

33. An apparatus according to any of claims 21 to 32, wherein the means for generating an image of the sample comprising means for generating a compositional image of the sample.

34. A method as substantially hereinbefore described with reference to the accompanying drawings.

35. An apparatus as substantially hereinbefore described with reference to the accompanying drawings.

ABSTRACT:

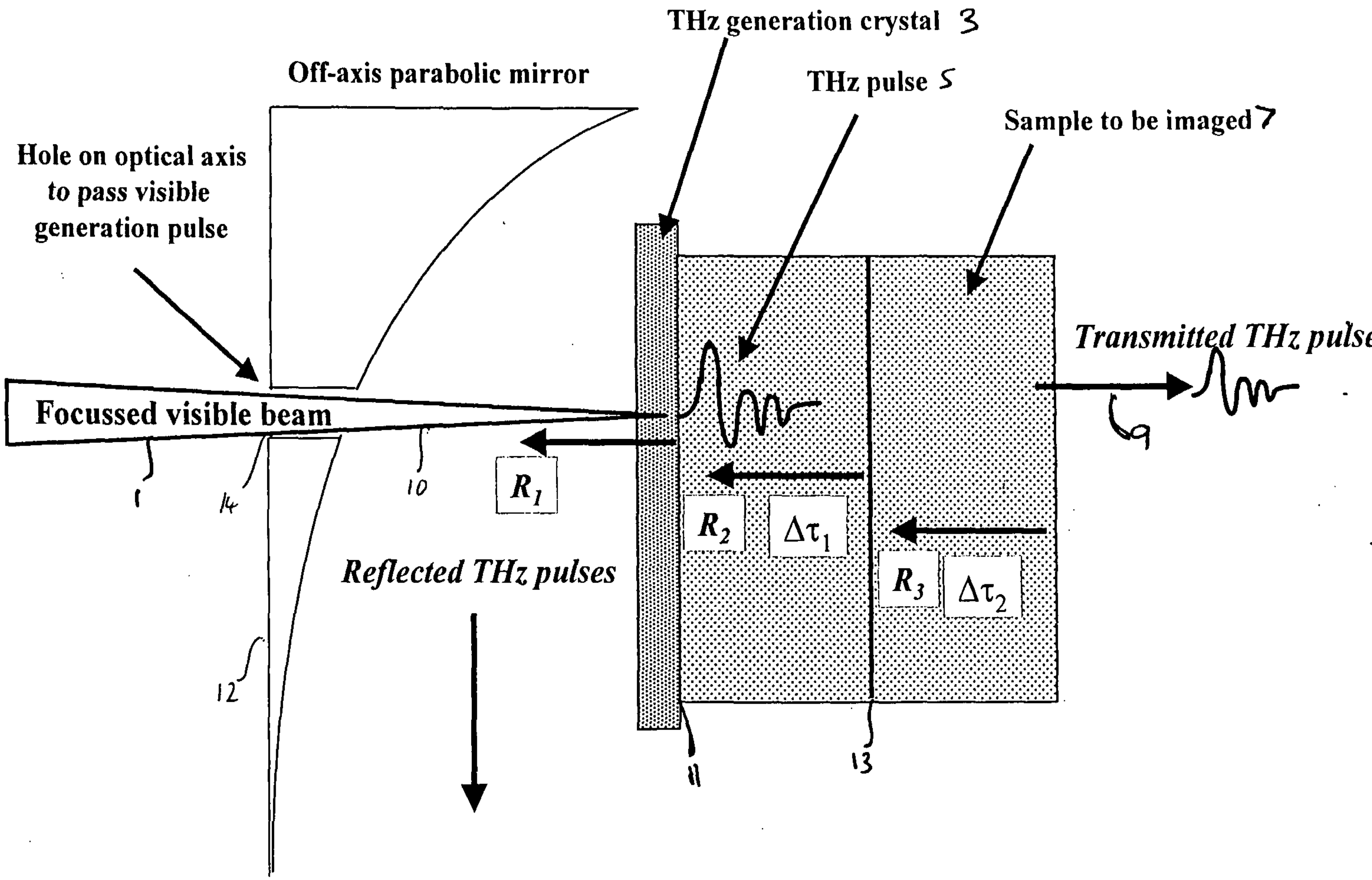
A method and apparatus for imaging a sample, the method comprising the steps of:-

a) irradiating a sample to be imaged with a beam of pulsed electromagnetic radiation with a plurality of frequencies in the range from 50GHz to 84THz;

b) detecting radiation which is both transmitted through and reflected from the sample; and

c) generating an image of the sample from radiation detected in step (b).

The method and apparatus can be used to generate a three dimensional image of the sample and/or a compositional image of the sample.



Version 3cc : June 99

FIGURE 1

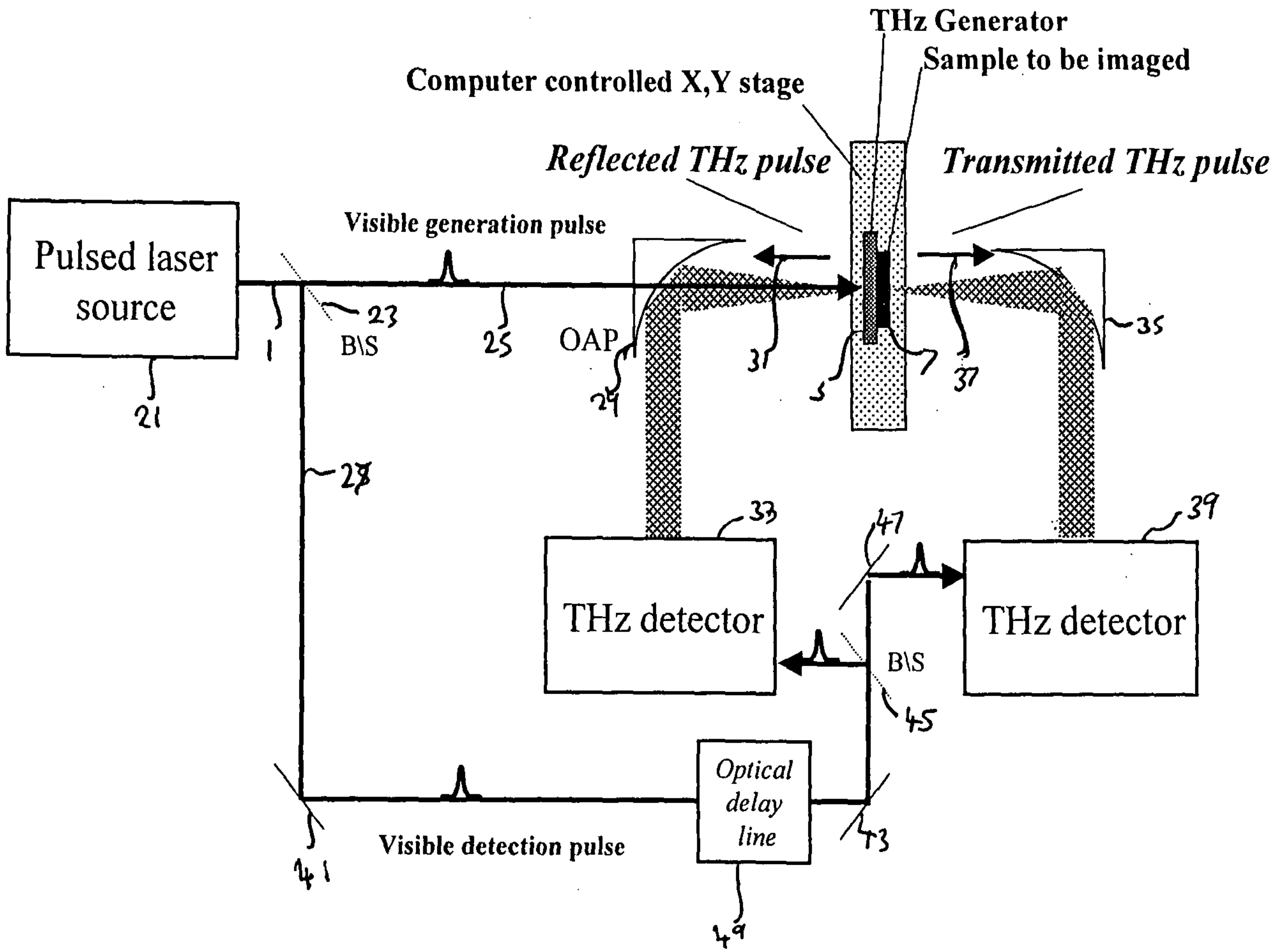


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FIGURE 2

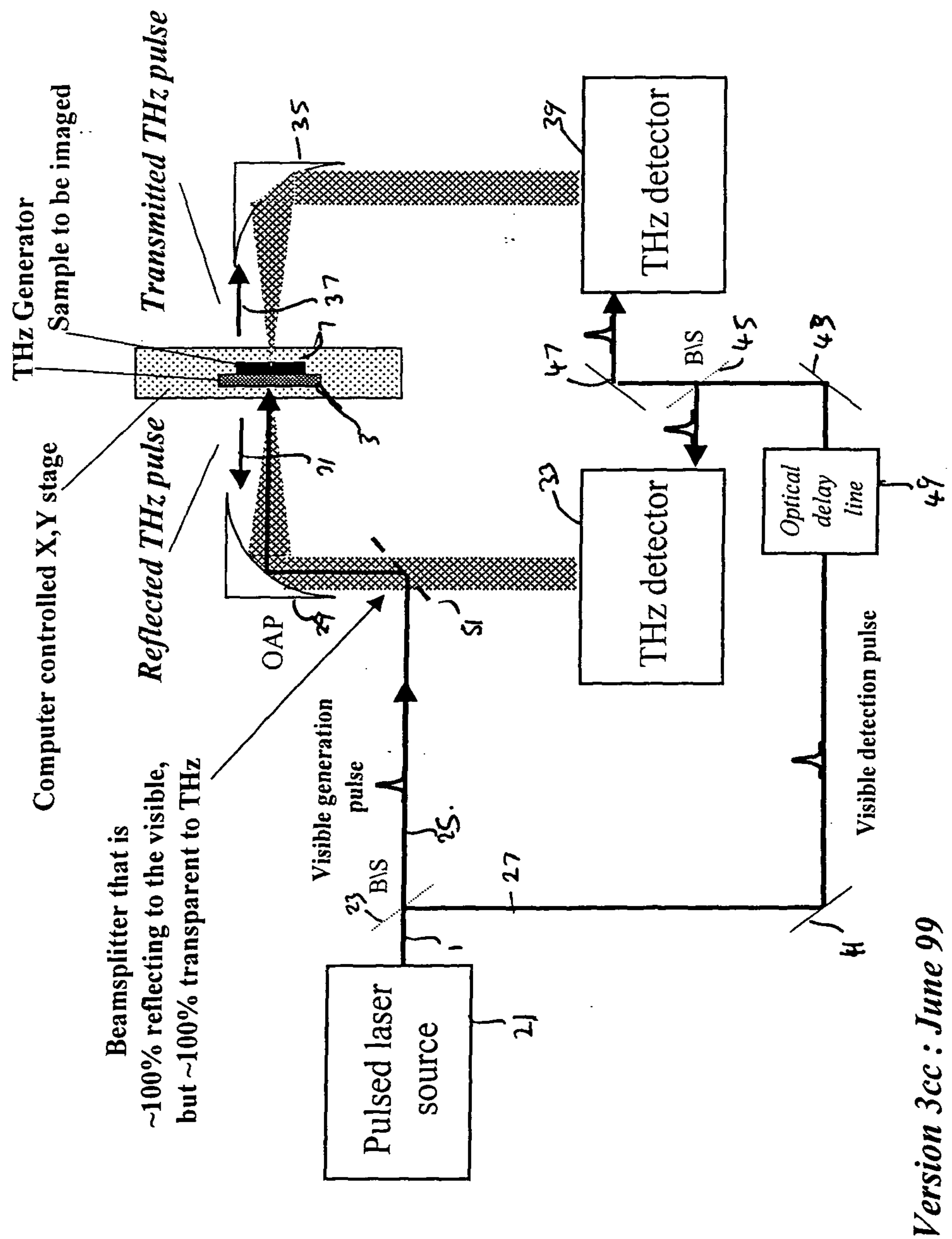
THz Generator
Sample to be imaged
Transmitted THz pulse
35
37
39
THz detector
Computer controlled X,Y stage
Reflected THz pulse
31
3
OAP
29
51
33
THz detector
47
B\S
45
43
Optical delay line
49
Beamsplitter that is ~100% reflecting to the visible, but ~100% transparent to THz
Visible generation pulse
25
B\S
23
27
1
Pulsed laser source
21
41
Visible detection pulse
Version 3cc : June 99

FIGURE 3

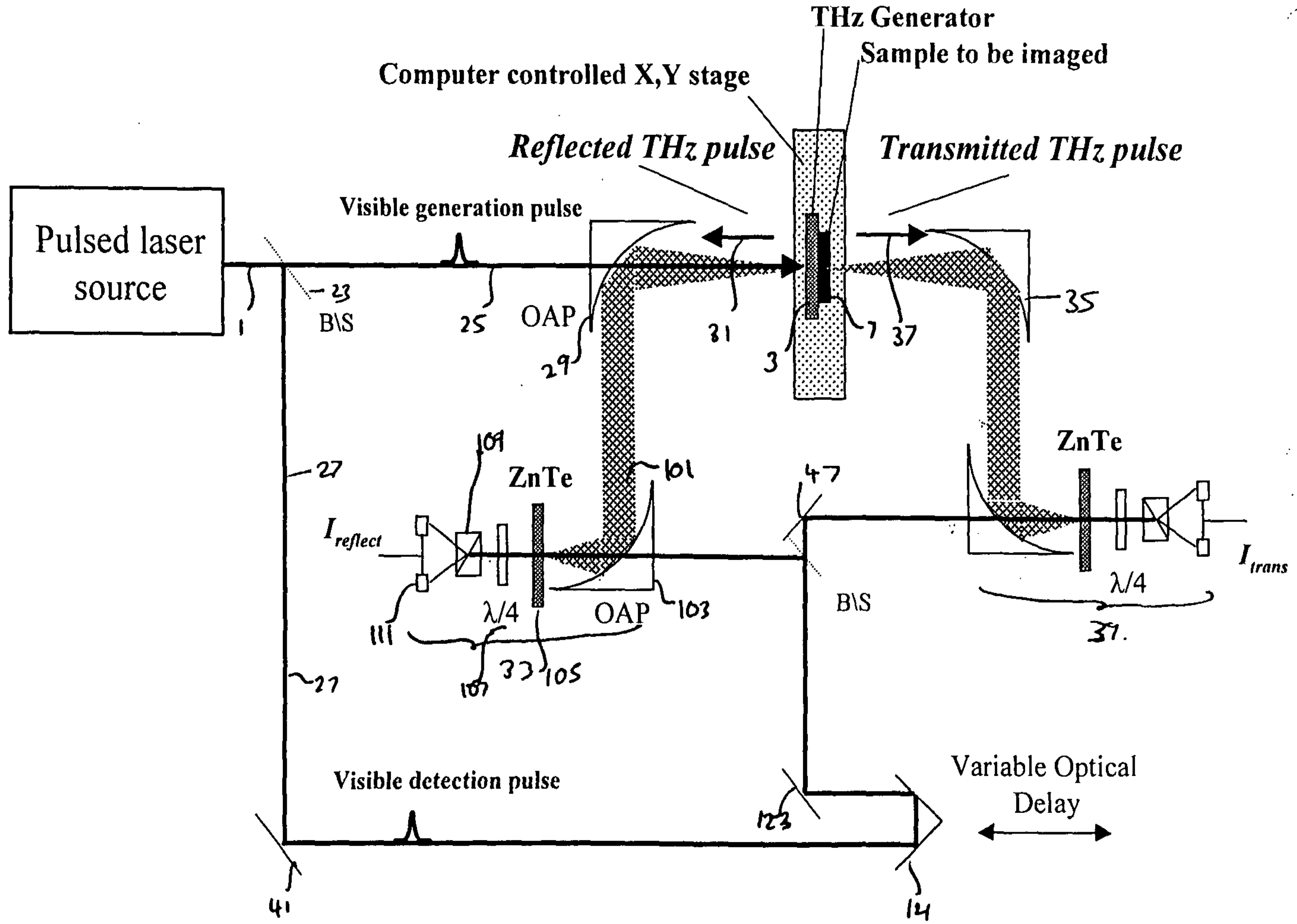

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FIGURE 4

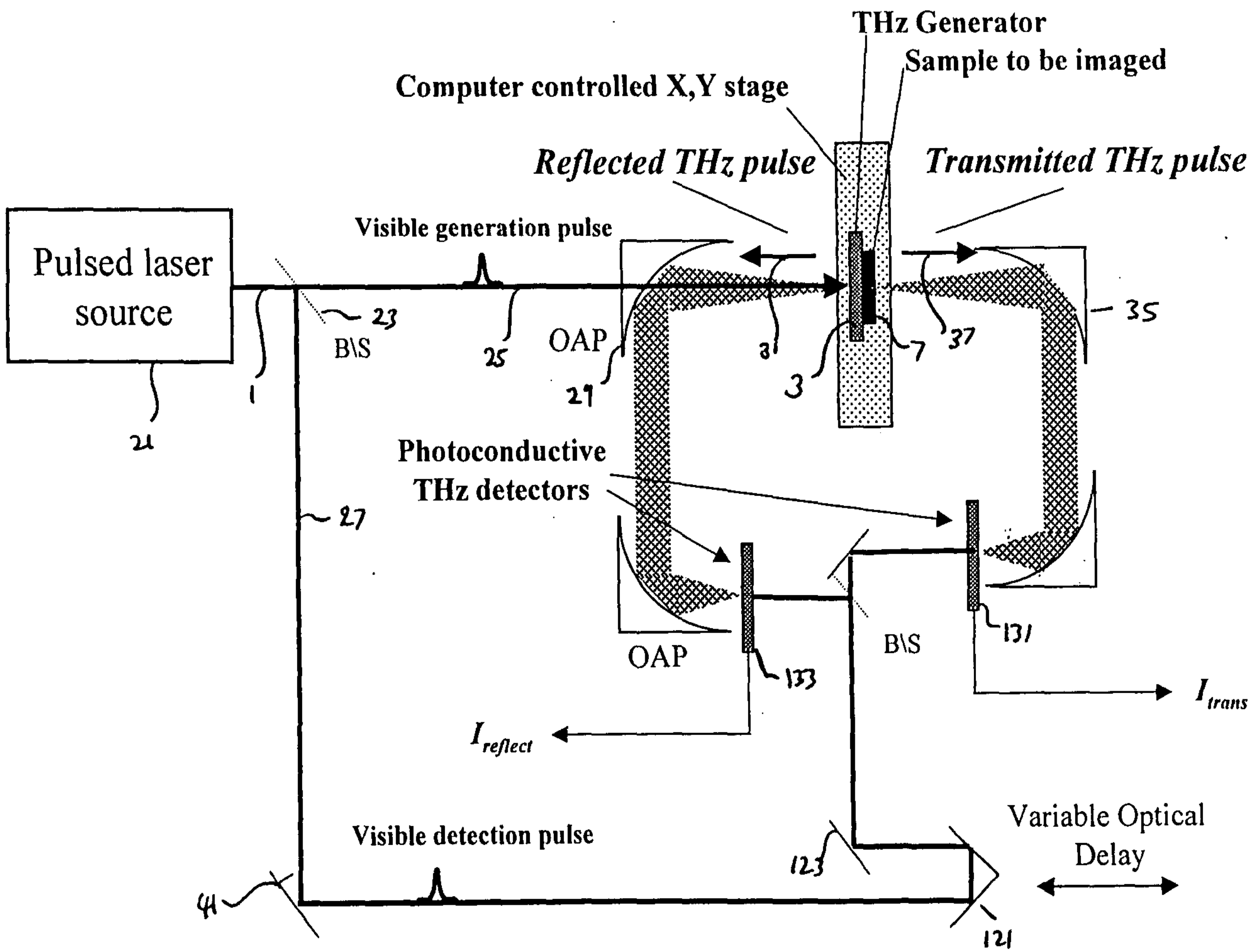

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FIGURE 5

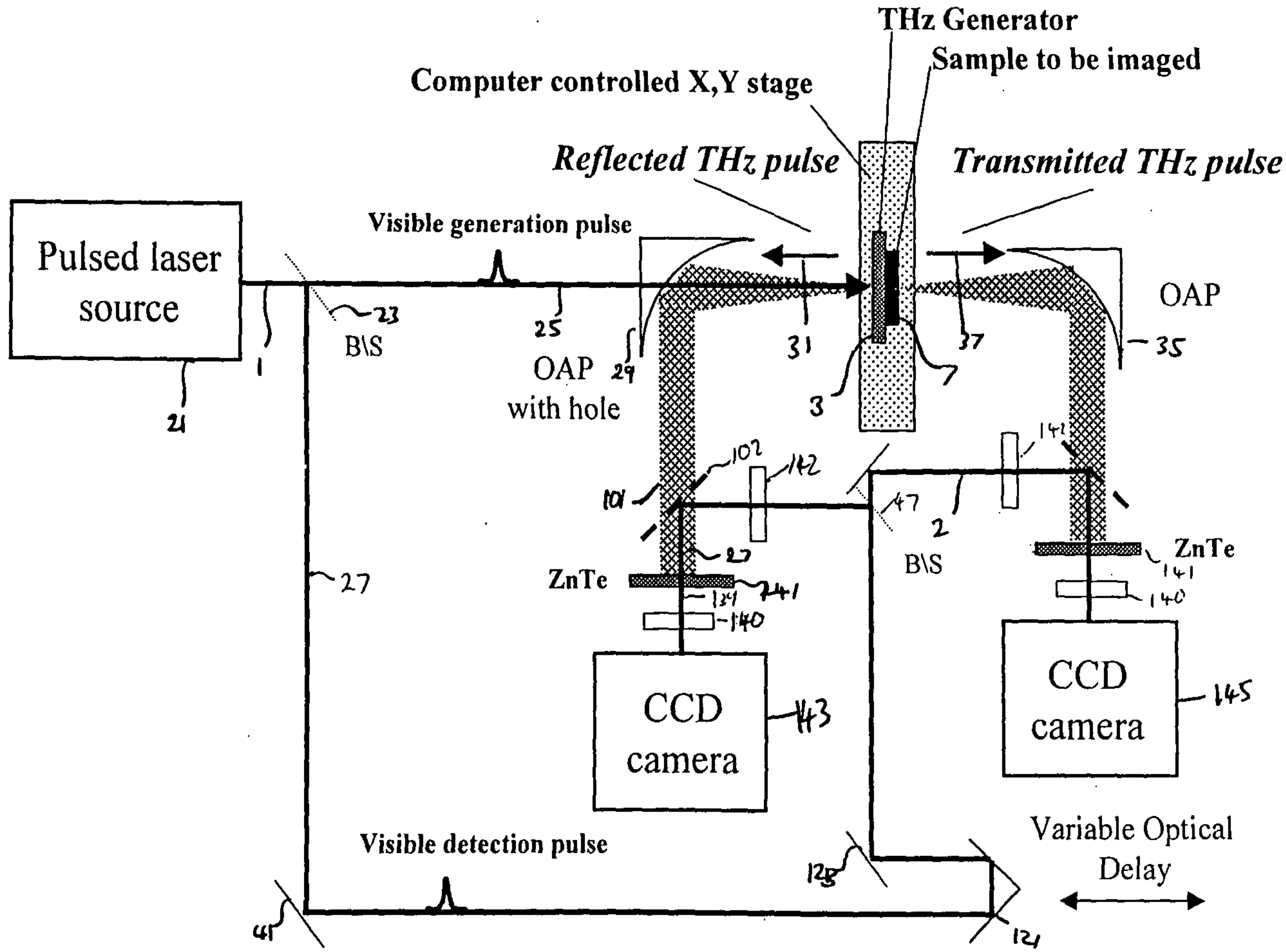

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FIGURE 6

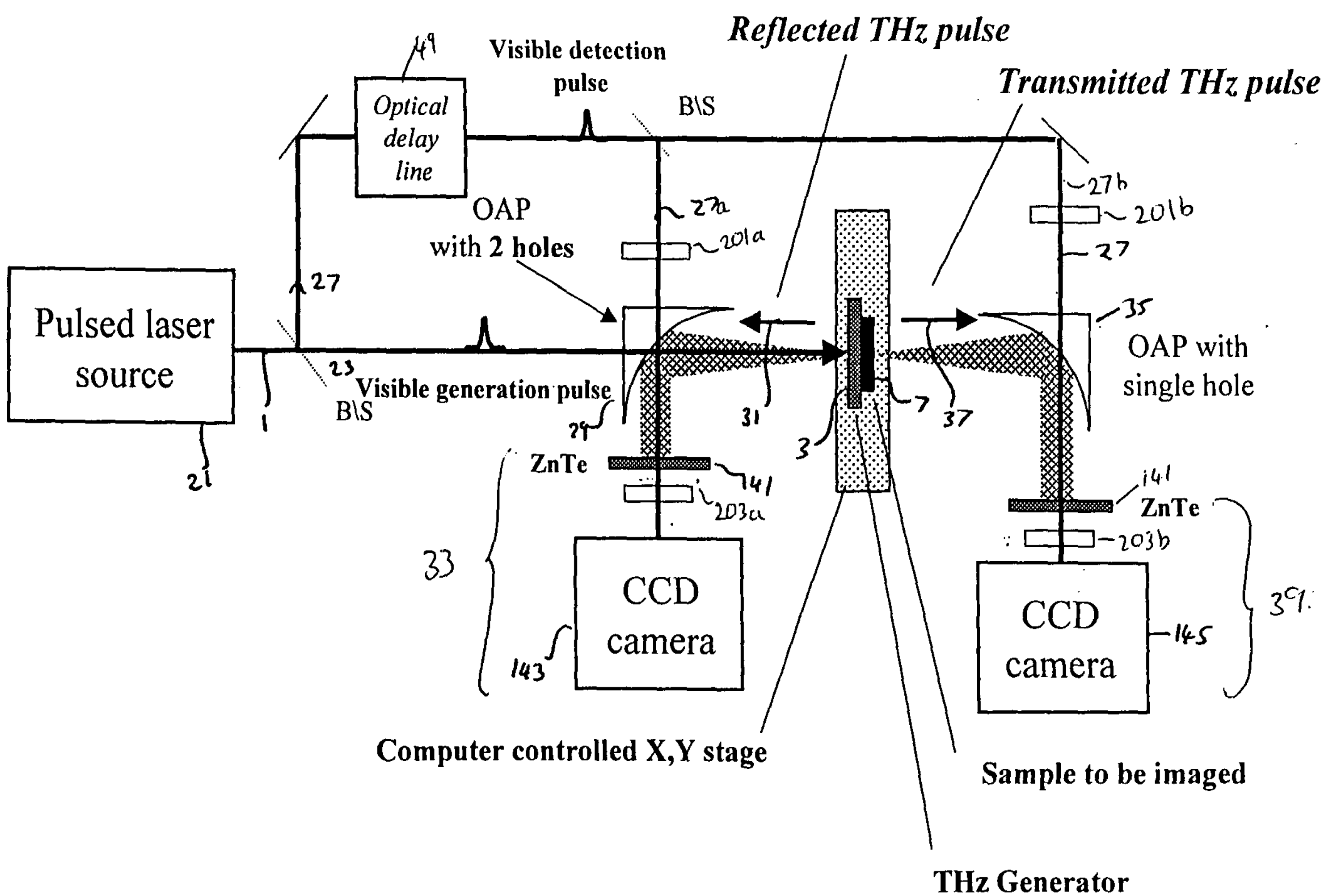

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FIGURE 7

7/9

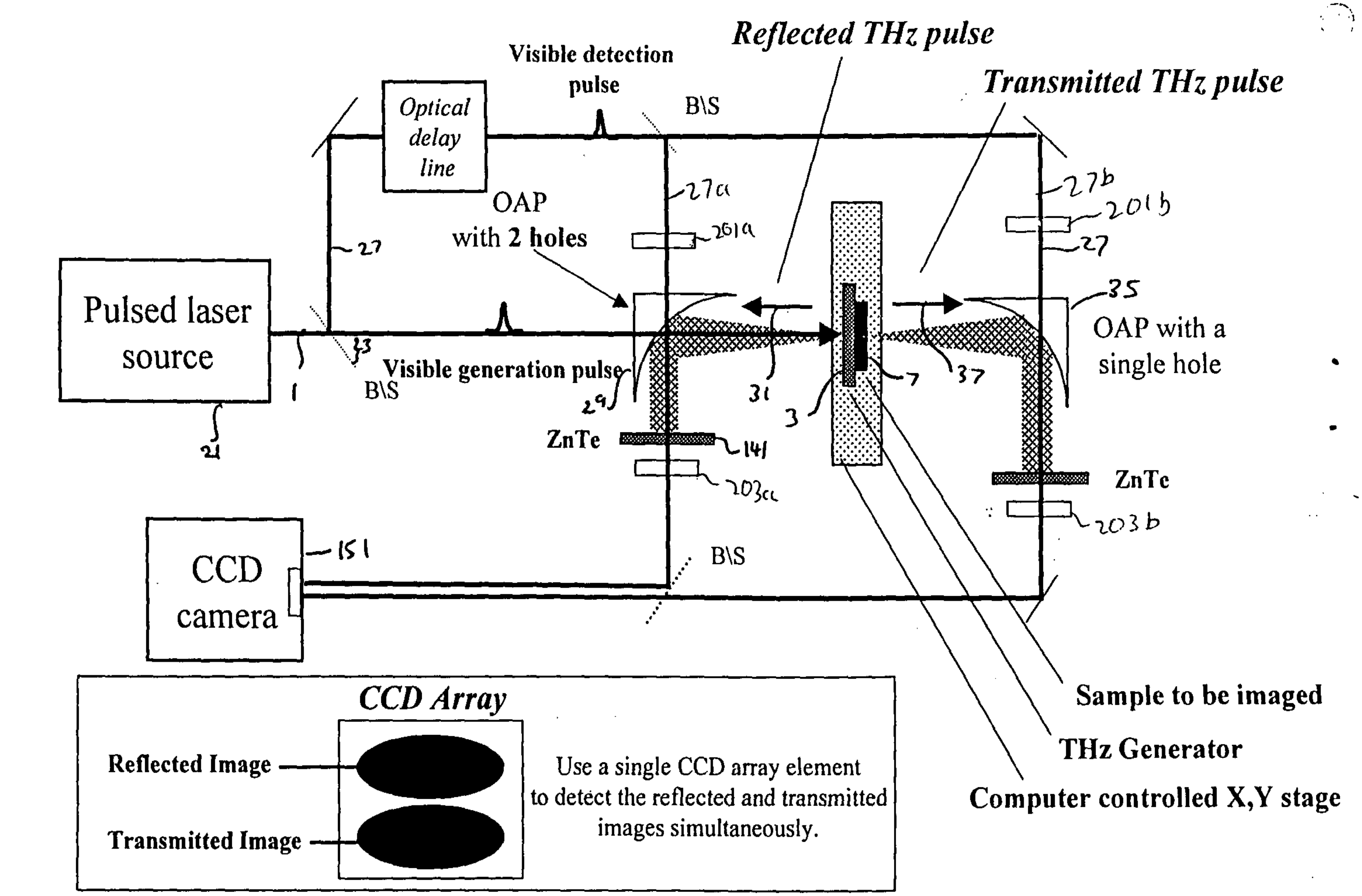

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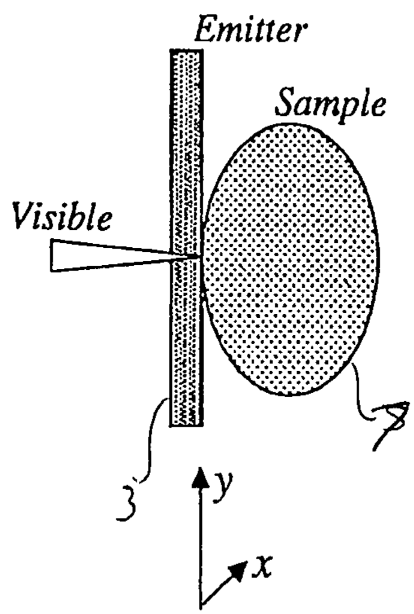
FIGURE 8

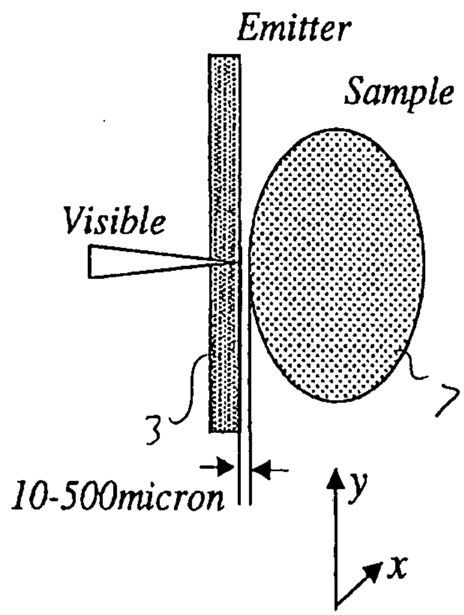
Arrangement #1



Sample and THz emitter are moved together using motorised stages.

9a

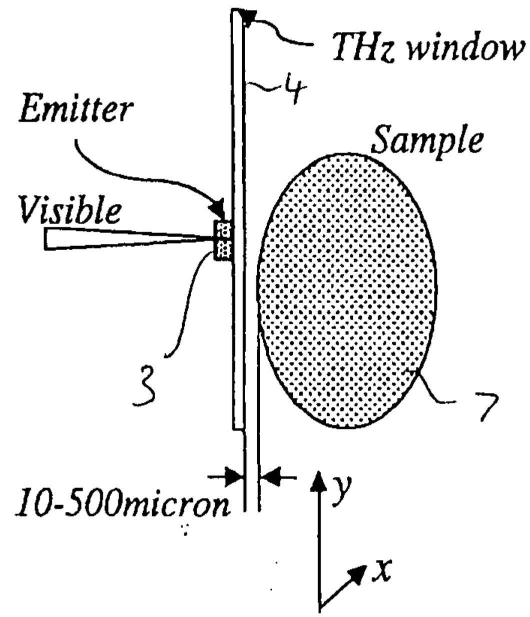
Arrangement #2



Small (10-500micron) gap between the sample and the emitter. Only the sample moves.

9b

Arrangement #3



Small emitter crystal, mounted on a THz window. The sample is mounted close (10-500 microns) to the THz window. Only the sample is moved.

9c

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FIGURE 9

Marks + Clerk